TECHNICAL UNIVERSITY OF LIBEREC
FACULTY OF TEXTILE ENGINEERING

THE EFFECT OF MOISTURE AND FINISHING ON THERMAL COMFORT AND SELECTED MECHANICAL PROPERTIES OF DENIMS WITH A PORTION OF SYNTHETIC FIBRES

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Mohammed Mushtaq Ahmed Mangat, MSc

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Symbol	Description
ω	Blood perfusion rate [l s^{-1}]
ρ	Density [kg m-^{3}]
q	Heat flow [W]
q''	Heat flow per meter square [Wm^{-2}]
λ	Thermal conductivity [$Wm^{-1}K^{-1}$]
W	Watt [J s^{-1}]
C_p	Specific heat [J kg^{-1} K^{-1}]
V_k l_k	Phonon group velocity, phonon free path
u	Velocity of elastic waves [m s^{-1}]
P	Porosity [1]
π	Pi
μ	Water ratio in fabric [1]
R	Thermal resistance [m^2K W^{-1}]
τ	Time of flow [s]
D_M *and* T_C	Fineness of weft and warp [tex]
d_M *and* d_C	Diameter of weft and warp yarns [m]
P_v	Fabric porosity [dimensionless number ratio]
D_M	Warp set [number of ends per meter]
D_C	Weft set [number of ends per meter]
ε	Fabric to fibre ratio (fabric density/fibre density)
F_w	Weight of wet fabric [kg]
F_d	Weight of dry fabric without moisture [kg]
λ_{AB}	Average thermal conductivity of fibres [$Wm^{-1}K^{-1}$]
h	Average fabric thickness [m] measured with the help of the Alambeta tester
R_a	Thermal resistance of air present in the fabric [m^2KW^{-1}]
R_f	Thermal resistance of fibre present in the fabric [m^2KW^{-1}]

R_w	Thermal resistance of moisture in the fabric [m^2KW^{-1}]
R_{ts}	Total thermal resistance of system (denim sample) [m^2KW^{-1}]
W	Agreement of the experts to evaluate the samples
b	Thermal absorbtivity [$Ws^{1/2}$ m^{-2} K^1]

List of constants

Thermal conductivity of water	0.58 [$W\ m^{-1}K^{-1}$] at 25 °C[1]
Thermal conductivity of air	0.0257 [$W\ m^{-1}K^{-1}$] at 25 °C[2]
Thermal conductivity of cotton [1]	0.4 [$W\ m^{-1}K^{-1}$] (its range is 0.3-0.5)
Thermal conductivity of polypropylene [1]	0.25 [$W\ m^{-1}K^{-1}$] (its range is 0.2-0.3)
Thermal conductivity of polyester [1]	0.3 [$W\ m^{-1}K^{-1}$] (its range is 0.2-0.4)

[1] http://www.engineeringtoolbox.com
[2] http://www.engineeringtoolbox.com

Abstract

This Study aims at the development of a model to predict thermal resistance of fabric under dynamic wet conditions and investigation of changes in thermal comfort and thermal parameters (conductivity, absorbtivity, resistance) of 180 denim samples made by using five types of weft, three sorts of weaves and 12 kinds of washing process under dry and wet conditions. It was found that thermal resistance model had a significant agreement with the experimental value and could be used for the prediction of thermal resistance of fabric made of different yarns under dynamic wet conditions. Various objective and subjective tests show that denim (functional denim) made by using spun polypropylene and cotton shows more resistance to drop of thermal resistance during wet conditions as compared to conventional denim and provide dry and warm feeling to user due to higher thermal absorbtivity. It has the highest moisture management capability. Besides that it provides higher moving comfort. Moreover, air permeability, bending rigidity, colour changes during industrial washing, subjective evaluation, coefficient of friction and geometrical roughness of denim samples were tested and found a scattered picture. Based on analytical values, it can be said that functional denim made by using cotton and spun polypropylene is a product that can be used under high wet and cold condition for better thermal comfort. In addition use of polypropylene reduces the quantity of required fibre for same thickness of denim due to its low density. Polypropylene replaces partially cotton for the denim manufacturers. Moreover, functional denim needs less water for washing and less heat for drying. Above all, it does not provide favourable environment for the growth of bacteria while wearing.

1 Chapter One

1.1 Introduction

The central subject of this Study is to develop a model for the prediction of thermal resistance of fabric under dynamic wet conditions. We have selected denim for the testing of our model due to its wide acceptance for the manufacturing of various clothing. Our second objective is the development and testing of functional denim able to stay warm and dry under wet conditions. For this purpose, we have used polypropylene and PET as weft yarn and cotton as warp. Moreover, we have compared different characteristics of functional denim with conventional denim, which is made by using 100% cotton yarn.

Literature provides a number of models for the prediction of thermal conductivity but model able to predict thermal resistance under dynamic wet conditions is still lacking. In addition to that, we could not find any model able to predict thermal conductivity and thermal resistance of fabric made by using different yarns.

One of the outcomes of this Study is a useful model that can be used to predict thermal resistance of fabric under certain dynamic wet conditions. Moreover, this Study has accomplished to weigh up effect of different combinations of fibres and application of variety of industrial washing process as well as type of weaving on the thermophysiological and sensorial characteristics of denim by using objective as well as subjective evaluation processes. The conclusion of the research is that there are certain combinations that can be used successfully to improve the comfort level of denim wearer extensively.

1.2 Problem statement

There is an obvious change in thermal conductivity and thermal resistance of fabric when it regains certain amount of water. This change is not linear due to many factors, which includes interaction between water and fibre, change in structure of the fabric, swelling effect, etc. This situation pushes to develop a model able to predict changes in thermal conductivity and thermal resistance. Such model is of much use for the manufacturing of clothing, which is used under sever wet conditions.

Moreover, during preliminary survey taken from the end users of denim garments a clearer observation showed that conventional denim made of 100% cotton becomes significantly damp in a high humid climate and it causes a sensible discomfort for wearer due to inherited high absorbent property of cotton. When there is an insensible moisture uptake, it provides better comfort but in case of sensible moisture, it provides a cool and humid feeling. There is a decline in thermal resistance due to higher thermal conductivity of water. This requires such denim able to withstand under dynamic wet condition and provide warm and dry feeling.

1.3 Aims and objectives

1. Model able to predict thermal resistance of fabric made by using different yarns under various moisture conditions and its verification by systematic testing of prototype denim samples.
2. Taking into account changes in fabric thickness and density due to water regain, while developing model for thermal resistance prediction.
3. Comparison of model with experimental values and finding a substantial agreement between simulated and experimental values.
4. Computation of the influence of moisture on thermal parameter of conventional and functional denim developed by employing distinct fibre composition, types of weave and application of commonly used textile auxiliaries.
5. Comparative analysis of air and moisture permeability, bending rigidity, geometrical roughness, moisture management capability, colour changes during washing and surface friction of conventional and functional denims.
6. Subjective evaluation of conventional and functional denim to ordain the difference amid the perception of people and the objective results.

1.4 Scope of the research

This Study is confined to the denim made of cotton and synthetic fibres and processed with various textile auxiliaries and their objective and subjective evaluation to compare thermophysiological and sensorial parameters under dry and wet conditions and development of a model for the prediction of thermal resistance under dynamic wet conditions.

1.5 Type of research

This is an experimental research; however, we applied simulation process to predict thermal resistance. The results of simulation was compared with the real values.

1.6 Research methodology

Literature survey was made to know the current state of the problem. Based on the guidance provided in literature, a model was developed for the prediction of thermal resistance of fabric under wet conditions. Moreover, 180 denim samples were produced by using three variable; types of weave, type of weft yarn and various industrial washing processes. Impact of type of weave, combination of different yarns and washing process on thermal parameters, bending rigidity, air permeability, vapour resistance, change in colour during washing was measured and compared. In addition to that subjective evaluation was also carried out for the confirmation of objective evaluation.

1.7 Contribution of study

This Study provides a model for the prediction of thermal resistance of fabric under various wet conditions. Moreover, testing of functional denim is the second outcome of the Study. Various tests prove that functional denim made by using cotton and polypropylene/polyester, provides better thermal comfort during wet and cold environment as compared to conventional denim made of 100% cotton.

1.8 Outline of the thesis

1. Chapter Two covers the theoretical part related to thermophysiological comfort, sensorial parameters and effect of dynamic moisture environment on thermal parameters and discussion about the various models under use.

2. Chapter Three deals with research methodology, sample development process, details of testing equipments and subjective evaluation process.

3. Chapter Four covers the data analysis and finalization of results.

4. Chapter Five presents the conclusion and recommendations for further studies.

5. Work of author and references have been provided in the last part of Study.

2 Review of current state of issues

Clothing comfort is required in all situations and is considered a threshold in choosing the clothing. Hohenstein Institute Germany buckled the clothing comfort science with a Greek philosopher *Empedocles*, 500 BC, who first time put forward his beliefs that human skin is breathing. Empedocles suggested that clothing should not depress the respiration and at the same time should not allow penetrating toxic elements into the body. At that time dress made by linen and silk was a dress of upper class and was considered as a precious fabric [2]. It shows that clothing comfort never remained out of preference of human beings. Nevertheless, clothing comfort became part of study in early 20th century when synthetic fibres were developed and more clothing that is functional were required.

2.1 Clothing comfort concept and definition

Clothing comfort is a state of mind when it is at its lowest stress level. Comfort is defined as the absence of perceived pain- and discomfort [3]. Min et al. [4] explain, “Clothing comfort is a state of satisfaction indicating physiological, psychological and physical balance”. Celcar et al. [5] say, “Clothing wear comfort is a state of mind influenced by a range of factors and is the result of a balanced process of heat exchange between the human body, the clothing system and the environment.” ASHRAE defines thermal comfort as an expression of mind that expresses satisfaction with the environment [6].

2.2 Thermal balance and comfort

Papkov [7] views the thermal imbalance as the core reason of discomfort and gives preference to discomfort instead of comfort. The feeling of discomfort is easier to define than that of comfort. Papkov further explains that in case when there is no removal of heat from the surface of skin, change in temperature in microclimate disrupts the activities of organs of human body and feeling of discomfort is the result to this. Papkov is of the view that nonexistence of discomfort is indication of comfort. Finally the concept of comfort can easily be presumed from the following statement, which is quite comprehensive:

> It [comfort] depends on many factors such as the temperature of the environment, the relative humidity, the wind velocity, the metabolism of the wearer and, of course, the

characteristics of the clothing materials, e.g. materials' thermal comfort properties, which display their abilities to transport heat and moisture from the human body's surface into the environment. The measuring values that reflect clothing's thermal resistance or thermal insulation, and water vapour resistance. Many other factors such as colour, fashion, an individual's physical and psychological state also give the feeling of comfort (Mecheels as cited by Celcar et al. [5].

Parsons [8] studied adaptation on thermal response due to gender, acclimation state, the opportunity to adjust clothing and physical disability. The results show that there is a significant difference. Nevertheless, difference is also a function of the temperature where it has been observed. It shows that comfort is feeling which depends on frequent physical and social factors.

2.3 Clothing insulation and its measurement

Thermal insulation is one of the basic requirements of any clothing [9]. Schacher et al. [10] have conducted studies on the impact of fibre thickness on thermal resistance. They found that fine fibre has low thermal conductivity and high resistance. There are many ways to measure it and many organisations have adopted different standards. Following list has been contributed by Al-Ajmia et al. [11]**:**

1. International Standards Organisation (ISO) [BS EN ISO 7730, 2005]
2. Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.
3. ASHRAE [ASHRAE Handbook, 2005. Fundamentals. Chapter 8. American Society of Heating Refrigeration and Air-conditioning Engineers, Inc., 1791 Tullie Circle N.E., Atlanta, GA.]

One of most common under use is *clo* defined under ISO 9920. In case of imbalance between body temperature and ambient temperature, we take help of clothing to get balance that is highly required for thermal comfort. ISO 7730[3] explains the details of thermal clothing and provides useful information how insulation works to provide thermal insulation for the protection of the human body from the cold environment.

Clothing insulation properties depend upon the type of fibre, yarn specification, fabric formation process and designing of clothing. Traditionally clothing insulation is measured in a unit that is called clo. It is equal to 0.155 [m^2KW^{-1}]. This value is almost zero for a naked person and for a business two-piece suit and accessories it is nearly 0.5 clo. The concept of clo is very customary in current times and is recurrently used to measure insulation properties of clothing described by Gagge et al. (as cited by Yan and Oliver [12]. Nevertheless, it is a relative meaure of thermal resistance of clothing.

clo is calculated under following conditions:

1. 58 Wm^{-2} Metabolic rate of a person in sitting position
2. 21^0C Ambient temperature
3. 10 cm s^{-1}air movement
4. 50% RH

Yan and Oliver [12] have put forward following equations Burton and Edholm to measure required thermal resistance for comfort:

$$l_{cl} = \frac{t_s - t_a}{H} - \frac{l_a(H+R)}{H} \qquad 2\text{-}1$$

Where, l_{cl} is resistance of thermal trasnfer in clothing comfort [clo units], t_s is skin temperature, t_a is air temperature, l_a is insulation of air, R is solar heat load on a humna [Wm^{-2}], H indicates dry heat transfer to environment (75% of metabolic rate) [Wm^{-2}], l_a [m^2KW^{-1}] is calculated by uisng the following equation:

[3] "ISO 7730:2005 enables the analytical determination and interpretation of thermal comfort using calculation of PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) and local thermal comfort, giving the environmental conditions considered acceptable for general thermal comfort as well as those representing local discomfort" (ISO).

$$l_a = \frac{0.1555}{0.62 + 0.19v^{0.5}}\left[m^2KW^{-1}\right] \qquad 2\text{-}2$$

Where, v is speed of air [cms^{-1}].

By using above equations, required thermal insulation [clo] can be calculated from the following eqaution:

$$l_{cl} = \frac{33 - t_a}{0.155H} - \frac{(H+R)}{0.62 + 0.19v^{0.5}}\left[m^2KW^{-1}\right] \qquad 2\text{-}3$$

Figure 2.1 provide thermal insulation values of different clothing.

Figure 2-1 clo values of different clothing (http://www.engineeringtoolbox.com/clothing)

2.4 Thermal balance and human body: A quantitative approach

Thermal balance is one of the central requirements for thermophysiological comfort. Many factors affect it and there is an un-ending effort to develop models to find out the correlation between these factors. Geršak and Marčic [13] have reviewed different models. Here are a few of those.

1. Clothing insulation model by Gagge, A.P., Burton, A.C., Bazett, H.C. in 1941. They introduced clothing comfort for measuring of clothing insulation.
2. Prediction Mean Vote (PMV) by Fanger in 1970, based on air temperature. Air velocity, means radiant temperature, and relative humidity, clothing insulation and activity level.)
3. J.A.J. Stolwijk multinode comfort model, based on six body segments: head, torso, arms, hands, lens and feet in 1970
4. B. Farnworth numerical model of the combined diffusion of heat and water vapour through clothing in 1986
5. Berkeley's multimode comfort model based on the Stolwijk model as well as on the work by Tanabe in Japan. This model takes 16 body segments.
6. Fiala presented a computer model that is based on a wide range of environmental conditions that was developed in 1999.
7. Song model uses numerical values and can be used in protective clothing. It was developed in 2004.

The description of all above seven models, throws light on various efforts of quantifying the thermal transfer and thermophysiological comfort. Nevertheless, it is a continuous effort, and still many people are trying to develop better models.

2.5 Measure of heat transfer under dynamic conditions

Calculation of heat and mass transfer (HMT), under steady state conditions are comparatively easy than under dynamic conditions. In real world, there is no steady state condition when a person is wearing clothing. There is a continuous change in the external and internal environment and this change is due to change in temperature and moisture on both sides of clothing. It becomes more critical when we measure it at micro level by dealing with the microenvironment available between the human body and clothing.

There are many instruments available in market for the testing of heat flow through fabric. Zhu et al. have conversed many machines used for this purpose [14]. Here we will give a brief of Zhu et al. findings.

In most of the machines, Pennes, skin model, which is written in the following way:

$$\nabla(\lambda_{skin}\nabla T)+\omega_b\rho_b\rho C_{p,b}(T_b-T)+q_m+q_r \\ =\rho_{skin}C_{p,skin}\frac{\partial T}{\partial t} \qquad 2\text{-}4$$

Where ρ_{skin} C_{skin} λ_{skin} represent the density, specific heat of blood and thermal conductivity of human issue, ρ_b *and* $C_{p,b}$ are the density and specific heat of blood, ω is blood perfusion rate, q_m and q_r are the volumetric heat due to metabolism and T is the human temperature. Authors have discussed many modifications in this parent equation, which was developed in 1948. Nevertheless, they have used a new skin model to measure the thermal performance of heat resistant fabrics. This instrument has been successfully used to assess the skin burn damage.

One of the most commonly used instruments is Alambeta. It is a non-destructive testing machine. Moreover, it can measure the thermal properties in a very short period. It is one of the testing equipments that measure thermal properties under various moisture percentages in fabric. It is mainly due to short time of measurement, in which we presume that there is a minimal variation in moisture percentage. Nevertheless, Alambeta does not measure moisture transfer.

Wang and Li [15] have developed an instrument able to measure mass and heat transfer properties of fabric under dynamic conditions. They have used the instrument to record dynamic changes of vapour pressure, temperature and heat flux. By using these values, they derived heat and moisture ratio and relative thermal diffusion ratio for final observation about heat and moisture transmitting property of fabrics.

2.5.1 Thermal conductivity, moisture and temperature

Work of Elansaria and Hobanib [16] is an advantageous effort to identify the relation between changes in moisture, temperature and thermal conductivity. They proved that there is a positive and near linear relation between temperature and thermal conductivity. Nevertheless, they used some food items for their study but we can apply it in fabric. It shows that in fibre, that has less specific heat values, becomes hotter than the fibre that has higher specific heat values, ultimately would lose their thermal resistance, and consequently would lead to a stage where human being has to feel less relief.

Kar et al. [17] have studied the impact of thermal and moisture transport properties of T-shirt fabrics on comfort sensations. They found that during different stages of exercises, fabric thickness, thermal insulation and warm/cool feeling of the T-shirt fabrics were important to warmth sensation. They further describe that water vapour transmission is not important to comfort sensations when a person starts exercise. Nevertheless, it becomes more important in the middle of the exercise up to the resting period after the running exercise. It may be due to high sweating. Indistinguishable is air permeability, which is not important in start and becomes significant at the end of exercise period. Zhongxuana et al. [18] have studied the impact of atmospheric pressure on thermal conductivity and found a reverse correlation. It is primarily due to the change in the gap between human body and the clothing. Higher gap to a certain extent gives better insulation.

Çay et al. [19] studied the impact of porosity on dye up take and found a significant correlation between dye up take and porosity (warp and weft density). It endorsed the observation of other authors that there is a strong correlation between porosity and moisture movement in the fabric. Higher moisture penetration helps in high yield of colour. Ruckman et al. [20] point out that we can make waterproof breathable fabrics, which play a crucial role in thermophysiological comfort. This is much important for outdoor jackets. It is worth noting that porosity is strongly related with breathability of fabric. There are many short comings attached with the model purely based on physics principle to forecast the thermophysiological comfort [21]. It shows that there is a strong need to add factors, which should cover matter related to human being.

2.6 Heat transfer and its measurement

In previous pages, we have discussed significance of heat and moisture transfer with respect to clothing comfort. In the following line, we will converse heat transfer phenomenon. This discussion will help us in understanding the heat flow between human body and environment through clothing.

Heat is something, which may be transferred from one matter to other following second law of thermodynamics. It is a quantity that can be measured and expressed in units. It is not a substance because it transfers from one substance to other and can change its shape (mechanical work). Heat is form of energy and its SI unit is joule [J]. It is also expressed in calorie, which is amount of heat required to raise the temperature of one gram of water from 14.5 degree Celsius to 15.5 degree Celsius. British Thermal Unit (BTU) is also a measuring unit of heat.

There are three methods for heat transfer:

- Conduction
- Convection
- Radiation

Nevertheless, evaporation is also used for heat transfer.

In this Study, we deal only with heat transfer through conduction. Discussion about heat transfer through convection and radiation is out of the scope of this study.

2.7 Heat Transfer through conduction

Heat transfer through conduction is a diffusion process. Amount of heat conduction depends upon the molecular arrangement, which includes space between them, their sizes and bonding, etc. Fourier's law of heat transfer through conduction in one direction describes that heat flow is directly proportional to a negative sign to the difference of heat at right angle through which heat passes. Furthermore, the amount of heat transfer per unit area is equal to the product of temperature gradient and thermal conductivity of the material. It can be interpreted in differential and integration forms.

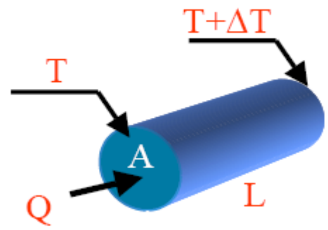

Figure 2-2 Flow of heat through a solid body [22]

Fourier's law is a discrete analogy of Newton's law of cooling, whereas, Ohm's law is an electrical analogue of Fourier's law. Following is the simplest form of Fourier's law:

$$q'' = -\lambda \frac{dT}{dx} \tag{2-5}$$

Where q'' is local heat flux [Wm^{-2}] λ is thermal conductivity [$Wm^{-1}K^{-1}$] and dT/dx represents the temperature difference along the line on x-axis, which is the thickness of the slab. In above equation temperature, which is a function of position and it, has been characterized in one-direction, displays that heat flow is a vector quantity. Above equation is based on a phenomenological law, which has been developed on the experimental values [23]. Negative sign indicates that heat flows from a high temperature to low temperature, since:

$$\frac{dT}{dx} = \frac{T_2 - T_1}{x_2 - x_1} \tag{2-6}$$

In above equation, T_2-T_1 is a negative value, whereas; x_2-x_1 is a positive value. This justifies the negative sign in the equation. It is also understandable from the Figure 2-3. The important point to note is that we are following heat flow notation given by Incropera and Dewitt in their book "Fundamentals of Heat and Mass Transfer". They use double-prime as an indicator of heat flux heat [Wm^{-2}] and lack of prime represents the amount of heat [W] over any appropriate area [24].

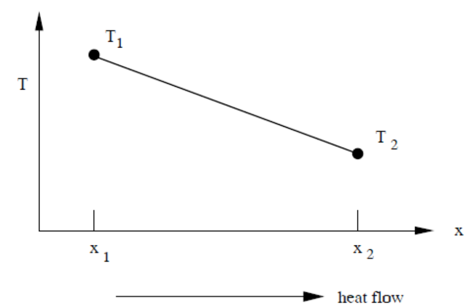

Figure 2-3 Heat Transfer from Higher to Lower Temperature [23]

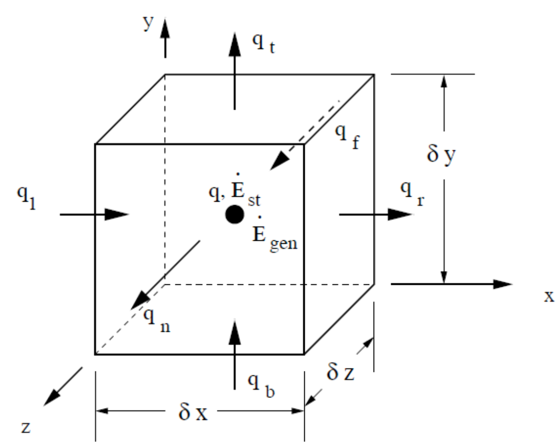

Figure 2-4 Differential volume depicts the arrangement of heat generation and heat flow in three directions [23]

Following equation represents the heat flux in three directions:

$$q'' = \lambda\left(\hat{i}\,\frac{\partial T}{\partial x} + \hat{j}\,\frac{\partial T}{\partial y} + \hat{k}\,\frac{\partial T}{\partial z}\right) \qquad \text{2-7}$$

The culminating purpose of heat transfer is the diffusion of temperature across the substance. It cannot be in one direction, however; the fundamental equation provides adequate information about the flow of heat in one direction. In case when we have to think over all spatial dimensions, Fourier's law does not provide enough information to calculate the temperature. For this purpose, we have to take assistance from energy conservation law (first law of thermodynamics).

Another issue related to heat transfer through fabric is the ignorance of heat transfer radiation. Other than conduction and convection, heat transfer through radiation is also possible. Heat transfer equation through radiation depicts that temperature plays a significant role in heat transfer. Hes et al. have [25] investigated effect of temperature on thermal conductivity and found that thermal conductivity increases due to the heat transfer through radiation. This shows that measuring of thermal conductivity by using different methods as described by Crow is not taking into account the portion of heat transfer through radiation. This missing may create a discrepancy between measured and simulated values. The share of radiation in total heat transfer from fabric is not more than 15% as put forward by Hes et al. [25]. Keeping this factor in view ignorance of share of radiation may not affect significantly the final values. In this Study, our focus is measuring of heat transfer through conduction, which is the main part of heat transfer from human skin to environment through clothing.

2.8 Prediction of thermal conductivity

An adequate theory for prediction accurately the thermal conductivity of polymeric melts or solids does not exist [26]. Simple phonon model of thermal conductivity is described by Krevelen and Hoftyzer [26]. Most of the semi empirical expressions for prediction of the thermal conductivity are based on the Debye equation [27].

$$\lambda = C_p \mu L \tag{2-8}$$

Where L [m] is the distance between the molecules in “adjacent isothermal layers” and u [m s^{-1}] is velocity of elastic waves (sound velocity). Assuming that L is nearly constant and independent on temperature, it may be expected that a direct proportionality exists between the thermal diffusivity D_T and the sound velocity u.

The process of thermal transport is supposed to occur in such a way that energy is passed quantum wise from layer to layer with sonic velocity and the amount of energy transferred is assumed to be proportional to density and heat capacity. No large-scale transfer of molecules takes place.

The thermal conductivity of matter is temperature-dependent. This dependence can be approximated by two phase empirical model [28].

$$\frac{\lambda(T)}{\lambda(T_g)} = \left(\frac{T}{T_g}\right)^{0.22} \quad for\ T \le T_g$$
$$\frac{\lambda(T)}{\lambda(T_g)} = 1.2 - 0.2\left(\frac{T}{T_g}\right)^{0.22} \quad for\ T > T_g \qquad 2\text{-}9$$

This model is in good agreement with experimental data. For amorphous polyethylene terephthalate it was found value 0.218 [$Wm^{-1}K^{-1}$)] and for amorphous polypropylene (atactic) it was found value 0.172 [$Wm^{-1}\ K^{-1}$] [28].

In highly crystalline solid polymers, the thermal conductivity is enlarged by a concerted action of the molecules. Crystalline polymers exhibit a stronger dependence of thermal conductivity on the absolute temperature *T* [K]. Eiermann [29] derived the simple relationship for polymers such as polyethylene polypropylene of “100% crystalline”:

$$\lambda = \frac{210}{T} \qquad 2\text{-}10$$

Therefore the thermal conductivity at room temperature of these highly regular polymers is found to be approximately 0.71 [$Wm^{-1}\ K^{-1}$] as compared with about 0.17 [$Wm^{-1}\ K^{-1}$] for the same polymers in the amorphous state. For the highly regular polymers the following empirical relationship can be used:

$$\frac{\lambda_c}{\lambda_a} \approx \left(\frac{\rho_c}{\rho_a}\right)^6 \qquad 2\text{-}11$$

Thermal conductivity at room temperature of fully crystallized polymers can be then simply predicted if ρ_c/ρ_a ratio is known. For the standard less regular, crystalline polymers the following relationship can be used to drive relationship [29]:

$$\frac{\lambda_c}{\lambda_a} = 1 + 5.8\left(\frac{\rho_c}{\rho_a} - 1\right) \qquad 2\text{-}12$$

Calculated heat conductivity of semi-crystalline polyethylene terephthalate at a common degree of crystalline of 0.40 is in very good agreement with the experimental value 0.272 [30].

Thermal conductivity of textile fibres is generally dependent on theirs chemical composition, technology of preparation (spinning and heat treatment), porosity and content of water. The results are scattered in some publications without description of measurements conditions.

Haghi [31] published values of thermal conductivity for some typical fibres. For practically non-porous polypropylene fibre he found 0.518 [$Wm^{-1}K^{-1}$] and for porous acrylic fibre 0.288 [$Wm^{-1}K^{-1}$]. For hydrophilic fibres is thermal conductivity based on the moisture content characterized by regain *RE* [%]. Haghi [31] found the dependence of thermal conductivity on *RE* for cotton fibres in the form of simple linear model. This model has error in order of conductivity because Rengasamy and Kawabata [32] found for dry cotton the value λ_{cot} 0.352 [$Wm^{-1}K^{-1}$].

2.9 Thermal conductivity of textile materials

Up till now, the discussion was about the basic methods of heat transfer and its related topics. In the next line, we will discuss heat transfer with respect to textile material. Thermal conductivity λ [$Wm^{-1}K^{-1}$] is an indicator of the ability of any material to conduct heat[4]. Higher values depict that heat will pass quickly, whereas, low values tell that heat will pass at a slow pace. Debye model developed by Peter Debye in 1912 is commonly used for the estimation of phonon in specific heat [33]. Debye equation to understand the thermal properties, is as under [26, 27, 34]:

[4] K is also used to represent thermal conductivity but in this report we will use λ instead of K to express thermal conductivity.

$$\lambda = \sum_{k} C_k \upsilon_k l_k \qquad 2\text{-}13$$

Where λ is the thermal conductivity, C_k V_k l_k is specific heat, phonon group velocity, phonon free path of mode k respectively. Militky [22] has quoted work of Van Krevelen and put forward the following equation to express the relationship between thermal conductivity and other parameters (see Equation 2.8):

In this equation, ρ is density, u is velocity of elastic waves, C_p is specific heat and L is average distance between molecules in adjacent layers. Above equation explains that thermal conductivity of crystalline material will be higher than the amorphous material. Heat transfer process is form of energy, which passes quantum wise between different layers of material with sonic velocity. Amount of energy transferred depends upon the density and thermal capacity of material. It is well understood from Debye equation as discussed in previous pages [30].

Epps [35] concluded that there was a nonlinear decline in thermal transmission and air permeable properties of fabric with the increase in number of layers. They further declare that fabric made of staple polyester fibre exhibits higher air permeability and lower thermal transmission. Nevertheless, fabric made of PET filament has low thermal transmission values. It shows that there is a difference in thermal conductivity and thermal transmission properties. In case of fabric, it is thermal transmittance not the thermal conductivity, since it is composed of polymers, air and moisture along with many other impurities, as quoted by Epps.

2.9.1 Thermal conductivity a non-linear behaviour of textile

Bigaud et al. [36] have discussed thermal conductivity tensor in detail. They conclude that modelling of thermal conductivity tensor is surrounded by the complexities, which are linked with inherited properties of material. Heterogeneous structure is one of the biggest issues that create lot of temperature variation within structure and heat uniformity depends entirely on the structure. In such situation constituents of the material, size and spatial arrangement of the material create a nonlinear behaviour the material when its thermal conductivity is measured.

Bigaud et al. [36] have used the following equation for the determination of anisotropic thermal conductivity tensor of the yarn-type meso-element (the fibre + matrix mixture).

$$\lambda_L = V_f\, \lambda_{fl} + [1 - V_f]\, \lambda_m \tag{2-14}$$

$$\frac{\lambda_T}{\lambda_m} = \frac{(1-V_f) + (1+V_f)\left(\dfrac{\lambda_{fl}}{\lambda_m}\right)}{(1-V_f)\left(\dfrac{\lambda_{fl}}{\lambda_m}\right) + (1+V_f)}$$

$$\frac{\lambda_T}{\lambda_m} = \frac{1}{4}\left[\sqrt{(1-V_f)^2\left(\frac{\lambda_{fl}}{\lambda_m} - 1\right)^2 + 4\frac{\lambda_{fl}}{\lambda_m}} - (1-V_f)\left(\frac{\lambda_{fl}}{\lambda_m} - 1\right)\right] \tag{2-15}$$

Where λ_L is longitudinal conductivity, λ_f and λ_{ft} are the fibre longitudinal and transverse thermal conductivity respectively, V_f is the fibre volume ratio, λ_m is the matrix thermal conductivity, λ_T is thermal conductivity of isotropic matrix.

In our case, testing material has a heterogeneous structure. In four samples, it has entirely different material on both sides (cotton on top and PP and PET at back). Moreover, there is a drastic difference in the structure and shape of fibre fineness. Keeping all difficulties in view comparison of thermal conductivity of different material is unwieldy.

Bogaty et al. [37] explain that there is a direct link between the fibre arrangement and fabric thickness. There is a certain change in the thermal insulation properties when pressure is applied. Nevertheless, the effect of pressure is different on a smooth and fuzzy surface. There is an understood change in the density of the fabric when pressure is applied while the main change occurs in the laying direction of fibres. Bogaty et al. conclude that wool and wool like fabrics are less sensitive to pressure. This study provides enough evidence that fibre arrangement and thickness have a significant correlation with thermal insulation.

Crow has described following methods to measure thermal conductivity of fabric [38]:

1. Cooling method
2. Constant temperature method
3. Disc method

In cooling method, a hot body is covered with the fabric and cooling rate of the body is measured. During this period, heat transfer takes place from the hot body through fabric due to radiation and convection. In constant temperature method, fabric is wrapped around a hot plate and heat is supplied to the plate to keep temperature constant. During this period, heat is allowed to pass through the fabric. Constant temperature methods serve for a long time to measure thermal insulation strength of the fabric. In disc method, fabric is placed between two plates that are kept at different temperature.

Above discussion clearly depicts that the heat transfer through fabric is not only due to conduction, whereas, it is a combine effort of conduction, convection and radiation. It is presumed that manufacturers of different instruments to measure thermal conductivity of fabric ignore the role of air present in the fabric and heat transfer due to radiation and conduction. As quoted by Crow [38], Morris reviewed all testing methods and proposed amendments in the measuring system.

Crow [38] says that thermal insulation of any textile material is far less than the air. Based on this observation, measuring of thermal resistance just by using the thckness and thermal conductivity is not a right method. Crow considers that heat transfer through fabric does not show its thermal conductivity, rather it is thermal transmission, and for measuring of thermal resistance one should not ignore thickness and density of the material. Furthermore, arrangement of the fibres and package density cannot be put aside during thermal insulation measurement.

Relationship among thermal insulation, thckness and the density is not linear and not simple. It is quite complex. Crow gives effect of change in density and thickness on thermal insulation and quotes many experiments conducted by adding more layers of fabric to increase the thickness, by putting more pressure to increase the density and testing of fabric of various thickness. It was found that by keeping density constant and increasing the thickness, there was an additive thermal insulation. In case when thickness reduced and density increased, they found a negative correlation with thermal insulation. Crow quotes experiment of Speakman and Chamberlain, which was reviewed by Peirce and Rees. In this experiment, thickness of low-density fabric was held constant and its density was increased. They found decrease in thermal insulation. This was due to the fact that thermal insulation of low-density fabric was approaching to the thermal insulation of air, which was quite height. In above experiment, increase in density has reduced heat transfer through convection and radiation and all heat transfer is through conduction. It is a known fact that conductivity of textile fibres is more than the air.

Crow [38] concludes that two factors, which play a significant role, are density and fibre arrangement. Parallel fibres give three times more insulation to perpendicular fibres. Moreover, there is no significant correlation between weight of the fabric and its thermal conductivity. However, thermal insulation may increase due to the increase in thickness, which is resulted due to increase in weight.

From all above discussion, we can presume that there are two main characteristics of fabric that play a key role in thermal insulation; amount of air present in the fabric, not only in the pores rather air preset inside the fibre and yarn. Second is the direction of the fibres in case of dry fabric. Nevertheless, presence of moisture can reduce the thermal resistance.

Crow discusses the effect of air between the human body and the fabric while wearing. He quotes that 4 mm to 10 mm is the right gap between the human body and the fabric for better thermal insulation. In case of wind, this gap is reduced and consequently, thermal resistance decreases.

There are some external factors, which affect the thermal insulation such as temperature and moisture in the air. Crow quotes that there is an increase of 0.5 clo if temperature decreases from 20 to -50 Celsius. Nevertheless, there is decrease in thermal insulation with the increase in humidity in the air. Furthermore, evaporation contributes a lot in reduction of thermal insulation. If there is no evaporation then there will be insignificant reduction in thermal insulation. There is a linear relationship between thermal insulation and moisture content in the material. Nevertheless, replacement of air gaps with Freon gas increases the thermal resistance three times, Crow quoted work of Matthew.

2.9.2 Thermal conductivity and porosity of textile

Major heat transfer between two surfaces of fabric is through conduction and less than 5% is through convection and radiation [39]. Generally, it may be true but in case of porosity, it may not work, because porosity can increase the share of convection and radiation. Sugawara and Yoshizawa [40] have conducted a comparison and found that porosity plays a significant role in thermal conductivity. They added that size and shape of pores have a significant contribution in thermal conductivity of any porous material. Sugawara and Yoshizawa have developed the following equation to determine thermal conductivity of any porous material:

$$\lambda = (1 - A)\lambda_s + A\lambda_f \qquad 2\text{-}16$$

Where:

λ - overall thermal conductivity of the porous material, λ_s *and* λ_f –thermal conductivity of solid and fluid respectively, $A = 2\frac{2^n}{2^{n-1}}\left(1 - \frac{1}{1 + P^n}\right)$, p is porosity, n is empirical component determined by mode of packing, pore size, pore shape and emissivity inside the pore n>0

Sugawara and Yoshizawa conclude that thermal conductivity of a porous material depends upon the thermal conductivity of fluid and solid. None of them can be ignored while measuring this. The main issue is the calculation of *n* values. It needs a lot of work and skill to develop this value for different materials. Moreover, Militky [22] provides latest development to measure thermal conductivity of yarn and fabric.

Pabst and Gregorova [41] have developed a second order relation between porosity and thermal conductivity. They claim that new relation is simple and easy to use and does not include complexities. Moreover, it is based on Coble–Kingery-type relation. The need to do modelling of thermal conductivity of porous material has been triggered by the use of much porous material for thermal resistance. Pabst and Gregorova have discussed the approach of Coble–Kingery, who have used the following impression for the prediction of thermal conductivity of a porous material:

$$\lambda_r = 1 - \frac{3}{2}P^2 + \frac{1}{2}P^2 \qquad \text{2-17}$$

$$\lambda = \frac{3(\lambda_0 - \lambda_1)}{2(\lambda_0 - \lambda_1)} \qquad \text{2-18}$$

Where λ_r is the reduced thermal conductivity and shows the ratio of effective thermal conductivity of porous material (λ) and thermal conductivity of Skelton (λ_0). Value 2/3 is first order coefficient and can be obtained by using case λ_1 = 0 (in case of gas phase where filling of the pores is negligible) and from the value of intrinsic thermal conductivity (λ) which is in the case of spherical inclusions, P is fractional volume (porosity).

Hollies et al. [39] investigated the flow of water in a fabric and in they concluded that movement of water in fabric or fibre follows the laws of capillary action. It is obvious from the results that water is carried out by the fibres through capillary action into the yarn. They have proved that water-holding capacity of fabric even made by using different fibres having the same structure is not same. It may be similar. This flow can be correlated with thermal resistance. Nevertheless, in all cases the main dependency is arrangement of fibres, which can reduce the capillary action rather than nature of fibres. These investigations support the observation of Sugawara and Yoshizawa that porosity, size of pores and shape of pores are the main contributing factors in thermal conductivity. We can conclude that arrangement of fibres and structure of fabric is more important than the type of fibres. For better understanding, we need to know something about diffusion of moisture.

Li et al. [42] point out the behaviour of hygroscopic and hydrophobic materials during absorption of moisture. They conclude that highly hygroscopic materials have less exchange of moisture with the surroundings, resultantly; they keep higher temperature prior to skin contact as compared to less hygroscopic fibres. Nevertheless, after coming in contact with the skin, they lose heat quickly as compared to others.

All above discussion depicts a complex situation. There is a multi layer and multi directional interaction among the type of fibre, arrangement of fibre, compactness of yarn, structure of fabric, fabric porosity, temperature, humidity in the air, pressure on the fabric, amount of air in the fabric and many more. There are a number of models available to resolve the situation. Lack of any model able to work in all conditions is obvious. For yarn thermal conductivity, it is assumed that yarn is in circular shape and there is a constant packing density then we can express the following relationship [22]:

$$d_c = -\frac{\sqrt[2]{T_c}}{\sqrt{10^6 \pi \rho_c}} \tag{2-19}$$

$$d_m = -\frac{\sqrt[2]{T_m}}{\sqrt{10^6 \pi \rho_m}} \tag{2-20}$$

Where:

d_c *and* d_m are yarn diameter of weft and warp and T_c *and* T_m are fineness of weft and warp and ρ_m, ρ_c are unknown densities of fibre.

It is obvious from all above critique and discussion that there are many factors which can alter the thermal parameters of fabric or even of yarn. All efforts are focused to predict thermal conductivity of fabric having distinct nature. It looks that accuracy is beyond the expectation. Nevertheless, there are chances to do prediction to a certain extent, Militky [22] concludes.

Zhu and Li [43] have developed a model by considering thermal conductivity as a function of porosity. Figure 2-19 depicts that there are seven types of resistances in the fabric. Moreover, it is obvious that some resistances are parallel and some are in series.

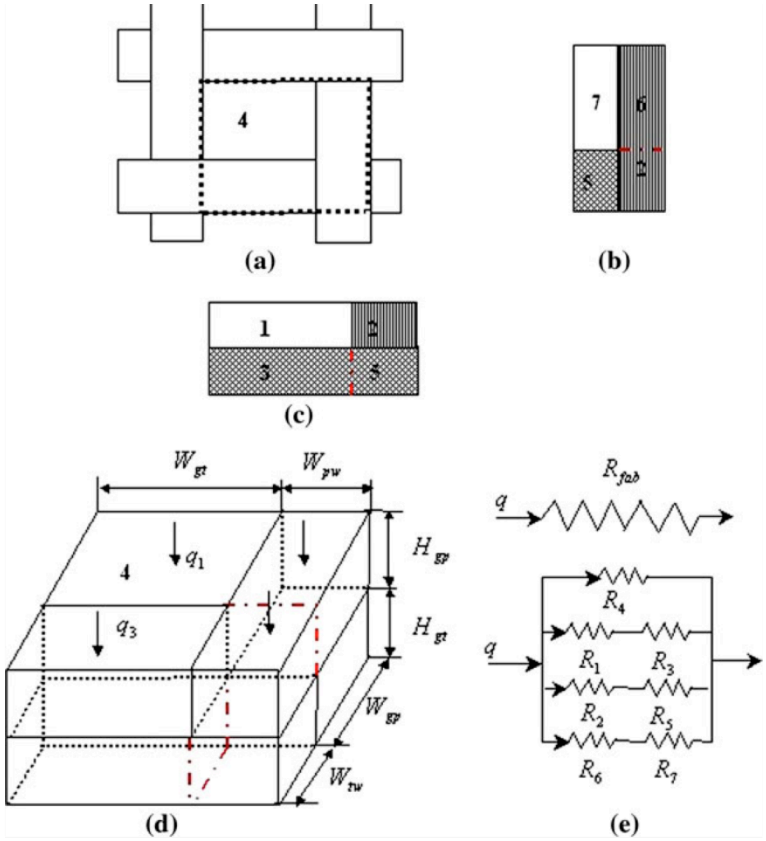

Figure 2-5 Structure of fabric [43]

(a) architecture of the plain woven fabric, (b) cross section along the weft direction for the idealized unit cell, (c) cross section along the warp direction for the idealized unit cell, (d) idealized plain woven unit cell, and (e) thermal resistance network [43].

Pores on the surface of the fabric are like small holes surrounded by the other substances. Number of such channels can be calculated by using the following equation:

$$N(L \geq k = (\frac{k_{\max}}{k})^{Dr} \qquad \text{2-21}$$

Where k is the pore size, K_{max} is the maximum size of the pore, L scale from scale law and D_f fractal dimension of the object. By using above equation, the pore size of unit cell in a fabric can be measured by using the following equation:

Equation 2-22

$$V_{fab} = L^{D_{fab}}$$

Where V_{fab} is pore volume in a unit cell. It tells that fractal dimension D_{fab} is:

$$D_{fab} = \frac{\ln V_{fab}}{\ln L} \qquad 2\text{-}23$$

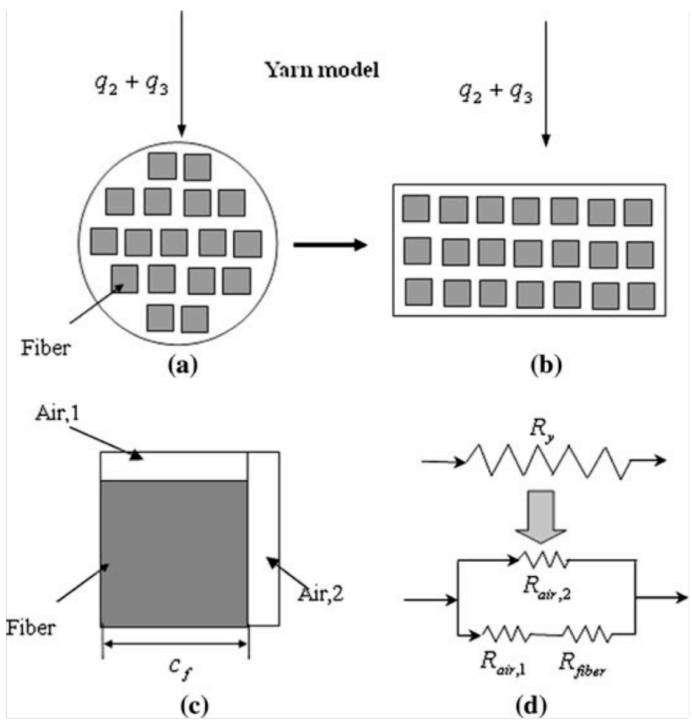

Figure 2-6 Structural model of yarn [43]

Structural model of yarn section: (a) idealized cross section of a yarn, (b) actual cross section of a yarn, (c) equivalent cell unit for yarn, and (d) heat resistance of unit cell

It is assumed that in some pores there is only resistance of air and in all other areas resistances are in series. There are many questions, which needed are to be addressed. The foremost objection is the ignorance of the micro gap with in the fibre. And the second point is the presence of air between the yarns. Nevertheless, their model is a reference point for the people working on thermal resistance of the fabrics.

There exists a plenty of various models for prediction of thermal conductivity of multiphase materials which can be used for prediction of textile fabrics thermal conductivity [22]. Militký [22] used the plain weave cell model for computation of volume porosity and then various two phase models for prediction of cotton type fabrics thermal conductivity.

2.9.3 Thermal absorbtivity

Warm-cool feeling of fabric is much important for the end users. People observe it during a short contact with fabric. Thermal absorbtivity ***b*** of fabrics was introduced in 1987 by Hes [3] to characterize thermal feeling (heat flow level) during short contact of human skin with the fabric surface. Providing that the time of heat contact τ between the human skin and the textile is shorter than several seconds, the measured fabric can be simplified into semi-infinite homogenous mass with certain thermal capacity ***ρc*** [Jm^{-3}] and initial temperature t_2. Unsteady temperature field between the human skin (with constant temperature t_1) and fabric with respect to of boundary conditions tenders a relationship, which permits to determine the heat flow q [Wm^{-2}] course passing through the fabric:

$$q'' = b\frac{(t_1 - t_2)}{(\pi\tau)^{.5}} \qquad 2\text{-}24$$

$$b = \sqrt{\lambda\rho C} \qquad 2\text{-}25$$

Where ρc [Jm^{-3}] is thermal capacity of the fabric and the term b presents thermal absorbtivity of fabrics. The higher is thermal absorbtivity of the fabric; the cooler is its feeling. In the textile materials, this parameter ranges from 20 [$Ws^{1/2}m^{-2}K^{-1}$] for fine nonwoven webs to 600 [$Ws^{1/2}m^{-2}K^{-1}$] for heavy wet fabrics.

2.9.4 Porosity and water in fabric

It is well known that thermal conductivity of dry fabric is mainly influenced by their porosity. The fabric porosity is a function of construction parameters as yarn fineness and set of weft and warp. There are many other factors, which can alter thermal conductivity of clothing. One crucial factor is presence of moisture in fabric. Increase of moisture percentage in clothing increases the thermal conductivity, which creates a cool effect. Increase in moisture percentage in clothing may be due to internal reason e.g. sweat of human or any external reason like, higher humidity in atmosphere or direct contact of clothing with water. Volume of fabric can be divided into main three categories:

Macro area consists of the warp and weft yarn and spaces between warp and weft.

Micro area consists of the inner parts of the yarn, space between fibre to fibre, opening due to textured structure of yarn, space in the inner side of fibre (amorphous region of fibre)

Surfaces of fabric, which has direct interaction with environment.

Volume of fabric is filled with polymers, water, air and any other foreign particles, such as textile auxiliaries etc. Final value of thermal conductivity and thermal resistance of fabric entirely depends upon the ratio and configuration of these substances.

Porosity indicates the ratio of fabric and fibre density. It is the area, which represents the space in the fabric. This may be at macro level or at micro level. It demonstrates the ability of fabric to trap air or water. Higher porosity means that fabric can trap more amount of air. Higher porosity means that fabric can have more space for air and water. Amount of water and air in fabric has a significant impact of thermal conductivity and thermal resistance. It shows that porosity plays a significant role in thermal resistance [22, 44-47]. Other than porosity, effect of surface roughness of fibre in wicking is quite significant [3]. Rough surface will complement in wicking and ultimately moisture absorbency will be increased. Work of Sugawara and Yoshizawa [40] is a classical example to measure the impact of porosity and temperature on thermal parameters.

They established a strong link between thermal conductivity and structure and temperature of the fabric.

Other than porosity Hes [3] has discussed the effect of surface roughness of fibre in wicking. Hes comments that rough surface will complement in wicking and ultimately moisture absorbency will be increased. More moisture means less thermal resistance. Keeping the point of Hes in view, the plane surface of PP and PET does not support the wicking process. Moreover, it does not provide enough space for water to stay.

Porosity can be defined as a ratio of projected geometrical area of opening and total area of the material. Cay [19] proposes the following equation to measure the porosity of the fabric:

$$P_v = \frac{open\ area}{total\ area\ of\ \ fabric} = \frac{D_M . D_c}{(D_M + d_M)(D_c + d_c)} \qquad 2\text{-}26$$

Where:

P_v is porosity and $D_M.D_C$ are ends and picks per unit length, d_m and d_c represent the diameter of warp and weft yarn. This equation gives geometrical expression of porosity. Nevertheless, in this definition porosity within the fibres and within yarns is ignored.

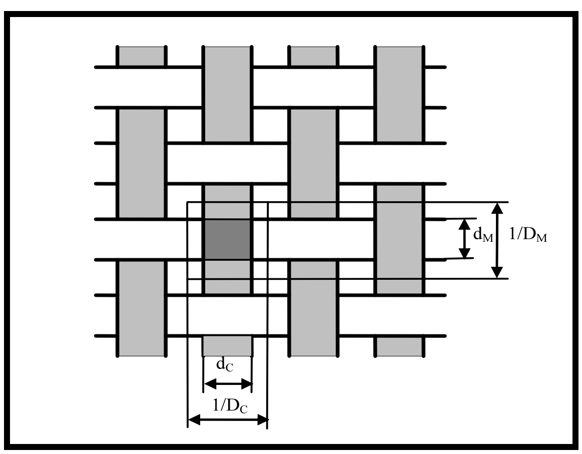

Figure 2-7Warp and weft configuration

For a more accurate calculation of porosity following equation proposed by Militky [22] can be used:

$$Pv = 1 - \frac{\left[d_c^2 D_c \sqrt{(1.16\, d_c^2 + D_c^2 + 1)} + d_M^2 D_M \sqrt{(1.16\, d_M^2 + D_M^2 + 1)} \right]}{4(d_c + d_M)} \qquad 2\text{-}27$$

Where:

D_M [1/m] is warp set, D_C [1/m] weft set, d_m *and* d_C are diameters of weft and warp.

For density computation Militky [22] proposes the following equation, which works better than simple geometrical porosity as given by Cay:

$$\varepsilon = \frac{\rho_w}{\rho_f} \qquad 2\text{-}28$$

$$\rho_w = \frac{W_p}{h} \qquad 2\text{-}29$$

$$\varepsilon = \frac{W_p}{\rho_f} \qquad 2\text{-}30$$

$$\rho_d = 1 - \varepsilon \qquad 2\text{-}31$$

Where:

P_d is porosity “density” with reference to density, ρ_w and ρ_f are the densities of fabric and fibre. ε represents the amount of fibre ratio in total system, Wp is planner weight of fabric [gm^{-2}], h is fabric thickness [mm]. For fabrics having more than one type of yarn, weighted average of different fibre density is taken.

For the calculation of density of fabric, planner weight of fabric has been used. It is obvious from above equation that porosity within fibres and between yarns has been also included here. This equation describes the porosity of the fabric. In other words, it tells amount of gap available in fabric that can be filled by air or moisture in fabric.

2.10 Thermal conductivity and thermal diffusivity

The heat transfer coefficient or thermal diffusivity D [$m^2\ s^{-1}$] is defined as [48].

$$D = \frac{\lambda}{\rho C} \tag{2-32}$$

Where ρ [$kg\ m^{-3}$] is density and C [$J\ kg^{-1}K^{-1}$] is specific heat capacity at constant pressure.

Thermal conductivity of solid particles has a huge variation. Metals have very high values. Thermal conductivity of polymers ranges from 0.2-0.5 [1]. It is important to note that there is a variation in thermal conductivity due to temperature. There is a significant impact of temperature on thermal conductivity of polymers. It can be explained with two phase empirical model [28].

Following equations can be used to measure ratio of thermal conductivity of different polymers having crystalline and amorphous structure:

$$\frac{\lambda_c}{\lambda_a} = \left(\frac{\rho_c}{\rho_a}\right)^6 \tag{2-33}$$

Moreover, following equation is suitable for semi crystalline polymers [49]:

$$\frac{\lambda_c}{\lambda_a} = 1.58\left(\frac{\rho_c}{\rho_a} - 1\right) \tag{2-34}$$

Above equation provides a significant agreement with the values measured by doing experiments [49].

2.11 Thermal conductivity of wet fabric

The main issue surrounds the heat transfer and thermal resistance in the presence of fluids such as water and air. There is a significant effect of moisture and air presence in the fabric. And moisture and air presence depends upon many factors such as chemical and physical structure. Moreover, it is hard to calculate the amount of fluids inside and onside the material.

Du and Li [50] have used Fick's law and established that fabric absorption velocity is in reverse relation with the warp and weft density. However, it does have a linear relation. It supports our findings that there is a non-linear change in thermal parameters when the fabric takes moisture. It is due to absence of a linear relation between pores and amount of water absorption.

Presence of fluids in fabric is multidirectional and it is on the surface. There is no such model able to cater the boundary effect of the fluids. However, we find one of the latest work by Militky [22].

Haghi [31] has presented two equations good for use to describe the effect of moisture on thermal conductivity. It is important to note here that as discussed by Crow in the presence of moisture and air, thermal conductivity measure of fabric, is not thermal conductivity, rather it is thermal transmission. However, for the sake of simplicity, we take it as thermal conductivity. Nevertheless, it is difficult to calculate the thermal resistance. Thermal resistance of the fabric can be influenced by the arrangement of the fibre and structure of fabric including level of porosity, types and size of pores. Here is one equation to calculate thermal conductivity of cotton presented by Haghi:

For cotton:

$$\lambda = (44.1 + 63.0\,\frac{\mu}{100})10^{-3} \tag{2-35}$$

Where:

λ represents thermal conductivity [$Wm^{-1}K^{-1}$] and μ is water ratio in wet fabric. In above equation, proposed by Haghi, we do not find thermal conductivity units on the right side of the equations. It shows that these equations cannot be used to predict thermal conductivity of cotton.

There is a linear relationship in moisture increase and thermal conductivity. The following equation has been used to measure thermal conductivity of cotton under various moisture contents:

$$\lambda(MC) = \left(1 - \frac{MC}{100}\right)\lambda_{\cot} + \lambda_{wat}\frac{MC}{100} \qquad \text{2-36}$$

Where, $\lambda_{\cot}(MC)$ is thermal conductivity of cotton in wet state, MC is water content in the cotton. Using above equation we can develop the following linear relationship between moisture content and thermal conductivity. Note cotton in shape of fibre can regain maximum 13% moisture at 90 % RH. After that there is no place to store the moisture.

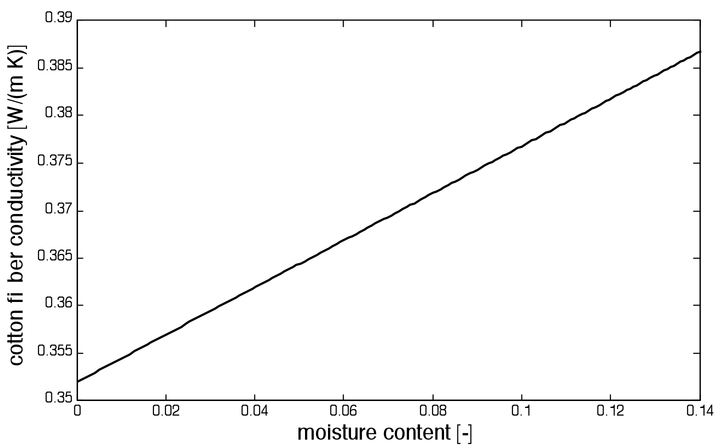

Figure 2-8 Thermal conductivity and moisture

In our case, we have added moisture as a third factor and simulated the situation not precisely based on any solid observation. Since we do not have enough evidence of the configuration of air, moisture and polymers.

2.11.1 Effect of moisture on cotton structure

Moisture regain depicts in the shape of weight increase. Walker [51] describes that there are significant changes in mechanical and chemical properties of cotton due to moisture regain.

There are many theories related to changes in structure of cotton. Walker quotes many theories and it was well supported by the data collected during 1928-29. Summary of work of Walker is presented here.

Due to reasonable moisture there are certain changes in cotton, it is mainly due to swelling. Particularly, there is a permanent change in colloidal gel of cellulose. It is apparent after removal of all moisture. Moreover, there is a drastic change in electric resistance due to minor amount of moisture.

Data shows that adsorption of moisture is a function of free hydroxyl groups. It was found that a minimum amount of hydroxyl was present there after the drying of cotton at high temperature. When cotton absorbs moisture, the hydroxyl groups which are oriented into the interior of the micelles due to rapid drying process. Due to this process, hygroscopic properties of cotton are neutralized by attraction of associated molecules. It is well illustrated in the hysteresis of wetting and drying process. The primary reason is that cotton structure does not get back to its original position in a rapid drying process.

Pore theory discussed by Urquhart and Williams (as quoted by Walker [51]) is another way to describe the changes. This theory explains that high insulation may be due to the pores present in cotton structure, which blocks the entrance of water molecules. Peirce initially proposed this theory in 1929.

All above discussion is related to electric resistance due to presence of moisture. In our case, thermal resistance is our main subject.

2.12 Thermal conductivity of heterogeneous material

Thermal conductivity indicates the ability of any material to pass heat from hot pint to less hot point. It shows that it is a function, which is carried out at micro level, but its effect is at macro level. Most common materials are composed of different substances. Availability of any substance in pure form is quite difficult. For example, iron, it has other impurities along with space filled by air or moisture. Compressibility of any material shows its porosity and space filled by air. Keeping this point in view, it can be said that most of solid materials have fluid (air) inside. Compression index depicts the ratio of solid and pores in any material. But in general, thermal conductivity is denoted as the property of material.

As discussed in previous pages, thermal conductivity is a function of speed of atoms, space between atoms or molecules, specific heat of the molecules and temperature of the substance. It shows any change in above-mentioned factors can change thermal conductivity of the material. Based on above consideration, thermal conductivity is a relative term and could be different in different conditions.

Moreover, direction of heat flow also plays a significant role in this matter. Work of Chu et al. [52] provide enough information about the thermal conductivity of composite material. Thermal conductivity is a combine effect of various factors. Most important are porosity and temperature [52]. Porosity does not mean a vacuum, rather it is area filled by air. Air available in environment is never 100% dry rather it is a mixture of moisture and many gases of different kinds. It is a known fact that molecular weight, space between the molecules and specific heat capacity has a strong influence on thermal conductivity. Based on this fact, it can be said that thermal conductivity of air is a combine effect of various factors.

One main question, which needs to be addressed, is the prediction of thermal conductivity of any material. People have tried to get mean value of thermal conductivity of different materials present in any compound. It may be fabric made of different materials, fabric with moisture, mixture of sand and stone etc.

We can put different materials together in various shapes. Few are mentioned here:

1. Different materials are places in series, double glazed window
2. Parallel arrangement of electric wires of different kinds
3. Random mixture of distinguish gravels
4. Powder in any liquid

Above figures provides information about the arrangement of different materials. In all cases, we can measure thermal conductivity as cohesive function of all substances present in the matters. Measuring of thermal conductivity of individual matters and then getting the average gives a false picture.

Chu et al. [52] conclude that small changes in interface of thermal conductance can alter thermal conductivity significantly. Their experiment is quite enough to believe that thermal conductivity of different composites could be different if there is a minor change in their sizes, which ultimately changes their interface with others.

Marmarali et al. [53] confirm the findings of Chu et al. They found a significant change in thermal conductivity of knitted fabric made of same yarn but having different planner weight and thickness. They proved that tight knitted fabric has higher thermal conductivity as loose knitted fabric. It is primarily due to change in interface and influence of gases, which have less thermal conductivity as compared to polymers.

Moreover, direction of conducting material also plays a significant role. It has been tested Yoshihiroa et al. [54]. They concluded that effective thermal conductivity of twill weave was double in the direction of thickness of twill than the direction of yarn.

Keeping all discussion in view, it is quite obvious, that any change in interface will create a big change in thermal conductivity of material and ultimately thermal resistance of the material. Finally, sum of thermal conductivity of different material is not possible. It does not provide the true picture. For example, we cannot have average thermal conductivity of a double glazed window by taking mean of thermal conductivity of glass and air. Values of thermal resistance by taking average thermal conductivity will be significantly different by summing the thermal resistance of air and glass. However, sum of thermal resistance of air and glass will reveal the right picture. We can add thermal resistance of the different material arranged in series or parallel. But when there is a random arrangement we have to take thermal resistance as a combine effect of material.

Sum of thermal conductivity of a heterogeneous material is not simple, particularly, in case when there is an interaction between diverse materials. For example, water in cotton fibre. In this case, there is a possible change in the structure of fibre. The following equation can be used for summing of thermal conductivity of diverse materials:

$$\lambda_{ab} = b_r \lambda_a + (1 - b_r)\lambda_b + I b_r (1 - b_r) \qquad \text{2-37}$$

Where *I* is interaction between a and b and b indicates the ratio of a and b in the substance.

Shastry [55] has discussed in length the thumb rule of adding thermal conductivity of different materials and concludes that lot of complexities attached with it. The most complex situation arises when there is any interaction between different materials. However, in case when we have cotton and polypropylene in any fabric, there is no interaction. Nevertheless, there is a friction between two. In case when there is an interaction, obvious is no linear relation. It may have different shape.

There is a need to find the effect of interaction between cotton fibre and water for precise calculation of thermal conductivity of wet fabric. Thus for the simplicity, Militky proposes the following equation to determine the sum of thermal conductivity of cotton and, polypropylene PET in denim under discussion [46]:

$$\lambda_{ab} = b_r \lambda_a + (1 - b_r) \lambda_b \qquad 2\text{-}38$$

Where:

λ_{ab} is combine thermal conductivity, b_r represents the proportion of fibre a.

2.12.1 Moisture in wet fabric

Charvát et al. [56] have investigated the transport of liquid in fibrous materials. They have used 3-D Ising model. This model fails to develop any ratio of water and air. Nevertheless, this model can elaborate the flow of liquid. In our case we need to know the amount of water and air and their location, in series or parallel. Surface area is more prone to evaporation as compared to inner area.

Following equation has been used to measure the proportional ratio of moisture in wet fabric:

$$\mu = \frac{F_w - F_d}{F_w} \qquad 2\text{-}39$$

Where, μ is water content in fabric, F_w is weight of wet fabric and F_d is weight of dry fabric without moisture. It is obvious from above equation that we have taken amount of moisture by considering the total weight of wet fabric as 1. It is not percentage; rather it is a proportion of water in total wet fabric and dimensionless. However, by multiplying it with 100, we can get the percentage of water in wet fabric. Moreover, we can use moisture regain by diving the difference with dry weight. People have used both ways to express the moisture [51]. Following equation provides water regain percentage:

$$RE(\%) = \frac{F_w - F_d}{F_d} * 100 \tag{2-40}$$

Moisture regain of any hygroscopic material is influenced by temperature. There are many models, which can be used for the prediction of moisture at various temperatures. Following relationship also gives estimate of moisture regain [57]:

$$RE(\%) = (0.8067 + 0.02912RH\sqrt[4]{100 - T} \tag{2-41}$$

Where, RE is moisture regain and RH is relative humidity in air. Under standard conditions (RH 65% and Temperature 20 °C) moisture regain of cotton is 8.074%. At this stage thermal conductivity is considered thermal conductivity of cotton. There is a variation in values of thermal conductivity of cotton. It is primarily due to the lack of standard conditions. Measurement in different context will provide different values. Moreover, there is a natural variation in different types and verities of cotton that has a significant impact on its thermal conductivity.

2.12.2 Moisture and density of fabric

There is significant impact of moisture in the structure of fabric, particularly made of hygroscopic fibres. Following equation can be used to predict the density of a cotton fibre under wet conditions. It is worth to note that density of cotton is 1540 Kgm^{-3}, whereas, density of water is 1000 Kgm^{-3}. In addition to that there is swelling phenomenon. Due to swelling, volume of cotton will increase and finally density will decrease.

$$\frac{1}{\rho_w} = \frac{\mu}{1000} + \frac{1-\mu}{\rho_d} \tag{2-42}$$

Where μ is moisture content.

2.13 Thermal resistance under wet condition

Thermal resistance is one of the crucial factors that contribute for better thermal comfort. It is imperative for design purposes of new fabrics and prediction of their thermal comfort. Fabrics are now and then used in wet state, but research reports on experimentally determined thermal comfort properties of fabrics in the wet state are not many [58-61]. We could not find any study dealing with thermal resistance due to change in moisture percentage. The reason of this situation probably depends on the fact, that common measuring instruments lack in measuring thermal parameters of wet fabrics, due to long time of measurement, during which the fabrics get dry. The instrument used in this study was the commercial PC evaluated Alambeta thermal comfort tester, which provides reliable non-destructive measurement of thermal insulation and thermal contact properties of fabrics in the dry and wet state, thanks to very short time of measurement [60].

Thermal resistance [m^2KW^{-1}] is directly proportional to the thickness and inversely proportional to the thermal conductivity [$Wm^{-1}K^{-1}$]. It displays that thermal conductivity plays a meaningful role in thermal resistance. Presence of water in fabric decreases the thermal resistance of fabric, which ends in the reduction of thermal resistance. Thermal resistance provides thermal comfort to the user by keeping the human body temperature intact. Nevertheless, at the same time, there is a need of removal of sweat from the human body. Otherwise, accumulation of sweat will start storing heat and will create a discomfort for the users.

Increase of moisture percentage in clothing decreases the thermal resistance, which creates a cool effect. It is primarily due to the lower thermal resistance of water as compared to fibres. Increase in moisture percentage in clothing may be due to internal reason e.g. sweat of human or any external reason like, higher humidity in atmosphere or direct contact of clothing with water.

2.13.1 Water and fabric

Presence of water in fabric is due to the following factors:

1. Van der Waals' forces
2. Electrostatic interaction

3. Solute molecules
4. Air-water interfacial tension in capillaries
5. Closed inter-yarn and inter-fibre space
6. Adhesion power of fibers
7. Hydrogen bonding

The most important factor in above-mentioned seven factors is the space between the fibres and yarns [47]. Water moves through yarn obeying the capillary action. Moreover, amorphous region of fibres also plays a crucial role in absorbing the water. It shows that porosity of fabric is most significant factor to change the thermal resistance of fabric.

2.13.2 Thermal resistance and moisture in fabric

Heat transfer from hot to cold body in all dimensions. In case of fabric, it is presumed that all heat moves in one direction due to small thickness of fabric as compared to its width and length. Fabric works as an insulating material and can be considered a second skin. Thermal insulation power of the fabric depends upon the type of fibre used and structure of fabric manufacturing.
In case of denim used in this Study, only 30% area of denim fabric is filled with polymers and the rest is composed of air. Air has thermal conductivity 10 to 15 times less than polymers and offers high resistance. In such case, heat flow is stopped by air but when this air is replaced with water, thermal resistance of the whole fabric reduces drastically.

Fabric has a certain structure and a finite thickness (height) and when its gaps are filled with water completely, it means that height of water column is equal to fabric thickness. However, in case when fabric has partial water, then the gaps are filled with water and air and we do not have any accurate information about the length of water column and length of air column.

Another problem attached with moisture is amount of water inside the fibre and water on the surface of fibres. Moreover, there is a change in the volume of the fabric due to swelling of fibre. There is an obvious change in the volume of hydroscopic fibres and this leads towards the increase of volume and holding capacity of the fibre as well as decrease the gaps between warp and weft.

Hes [59] has discussed in depth the effect of moisture on thermal resistance and concludes that porosity of the fabric plays significant role in thermal resistance. He adds that structure of fabric is more important for higher thermal resistance than polymers. Observation of Hes has been confirmed by having a variation in the values of thermal resistance under two different pressures. It shows that more compressible structure has higher thermal resistance.

Keeping all difficulties in view, we have adopted the Militky equation to measure amount of water and air in the material by using densities of water and polymer.

2.13.3 Fabric structure and thermal resistance

Fabric surface area can be divided into five categories:

1. Free length of warp (cotton)
2. Free length of weft (synthetic yarn)
3. Intersection of warp and weft
4. Pores filled by air
5. Pores filled by moisture

Thermal resistance of all above five areas is different with one another because of chemical and physical structure, porosity of the fabric, arrangement of warp and weft. Moreover, there is a big difference in yarn package density of warp and weft. In addition, precise calculation of the all-different areas is quite difficult, due to the various loopholes, mainly, yarn structure, its shape etc. Özdil et al. [62] have studied the impact of yarn and fibre fineness and other parameters on thermal properties and found a significant correlation. Keeping all in view it is apparent that there will be many changes in thermal parameters due to changes in fabric construction.

Hes et al. [63] conducted a study to measure effect of moisture on some smart underwear knitted garments. This study concludes that a blend of hydrophobic and hydrophilic fibres presents advantageous clothing comfort under wet conditions. It is mainly due to the superficial attachment of moisture. Hes et al. further point out that shirts made of 100% cotton, retain more water, lose its thermal resistance, and become a reason of cool effect. This study provides a guideline about the flow of heat through a fabric having asymmetric kinds of warp and weft.

Sadikoglu [64] has studied role of hygroscopic material to keep human skin dry-hand and found a strong correlation. In our study, we are using different fibre compositions and trying to find out the correlation. Li et al. [42] have studied the fibre hygroscopic behaviour and perceptions of dampness. They found that in above saturation level, drying speed of wool and polyester is same and difference occurs below the saturation points. It means that fibre having higher saturation point will become dry later as compared to fibres having low saturation point. This is the key factor that PP which has low saturation point and becomes dry soon and keeps its thermal conductivity low since there is less water in it as compared to other cotton and PET.

Yoshihiroa et al. [65] is another example which clarifies that there is a definite difference in thermal conductivity of fabrics having different structures. Study depicts that direction of measurement (transverse or longitudinal and in direction of thickness) also changes the value of heat flow. It reinforces the observation that direction of material also plays a critical role in heat flow property of fabric.

Keeping all obscurities in view, following simulation has been chosen to measure the thermal resistance. Figure 2-9 presents the heat transfer through different materials arranged in series and parallel. In both cases net heat flow will be different due to the summation of thermal resistance, which is different in both cases.

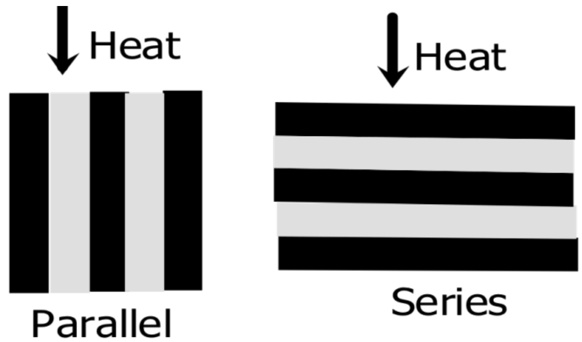

Figure 2-9 Heat flow parallel and in series [22]

Figure 2-10 Arrangement of warp and weft along with spaces filled by air and moisture [66]

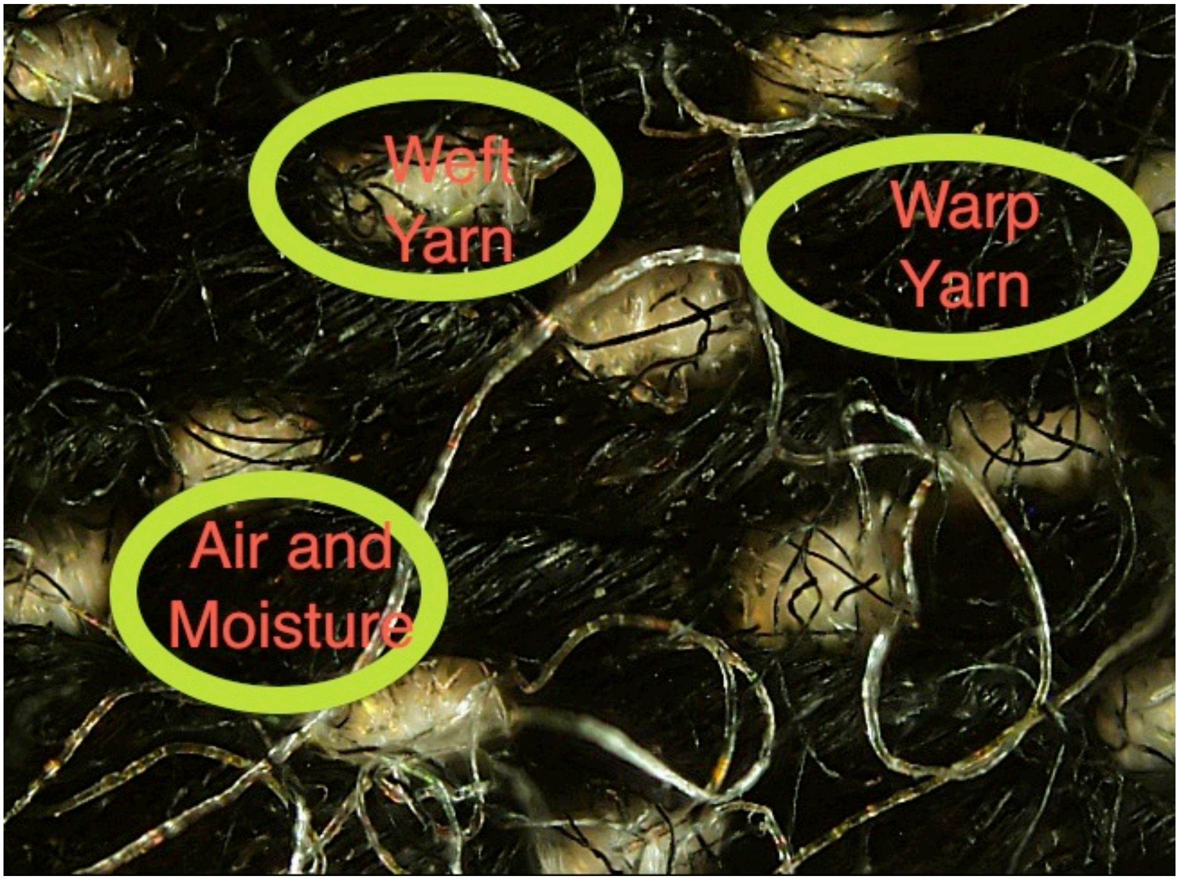

Figure 2-11 Reverse side of denim

It is presumed that fabric is composed of fibre, air and moisture. Amount of pores can be calculated by using Militky equation of porosity "density". This equation gives us the ratio of fibres and porous area.

2.13.4 Total thermal resistance of wet fabric

Fabric is composed of:
polymers,
air
moisture (inside the fibre)
It is important to note that water in fabric is mainly due to absorbent nature of fibre. All have different thermal conductivity and different thermal resistance. To quantify the total thermal

resistance of different materials in fabric, we have to follow method used in electricity to sum up the resistances. According to this method, resistances are in series are just added and if these are parallel, then their reciprocal is added.

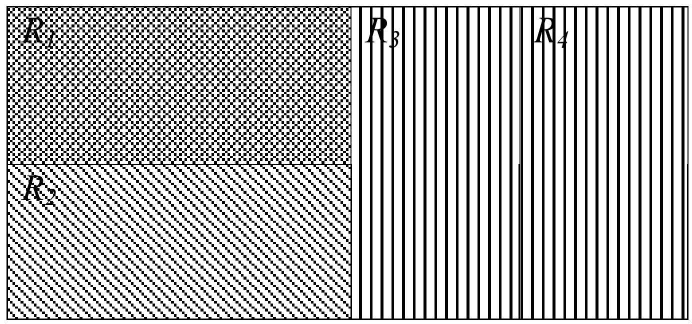

Figure 2-12 Resistance in series and parallel

Figure 2-12 depicts arrangement of resistance. R_1 and R_2 are in series and R_3 and R_4 are in parallel. It has an analogy with electric resistance. Total resistance in both cases will be as follows:

Resistance in series:

$$R_t = R_1 + R_2 \tag{2-43}$$

Resistance in parallel:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} \tag{2-44}$$

2.13.5 Fabric compressibility and Alambeta settings

Alambeta has two settings for pressure; 200 Pa and 1000 Pa. During initial testing, it was found that there is a significant difference in the thickness of fabric when it is measured under two different weights. There is big difference in thermal resistance. It is mainly due to the difference in thickness. It is important to note that all onward values taken by using Alambeta at 1000 Pa pressure.

There is a lot of hairiness on the surface of fabric. There are many models, which measure the amount of hairiness on the surface of the fabric. One of the famous models is by Neckar.
According to Neckar model, following five types of fibres are present in the yarn:

1. Fibre ends
2. Loop
3. Protruding fibres
4. Reversal ends
5. Reversal loop

Moreover, Voborova et al. [67] provide enough information about the hairiness and the twist. They proved that TPI has a strong impact on hairiness. In denim, open-end yarn has been used, which has low TPI. Consequently, fabric made of such yarns possesses more hairiness.

The packaging density of textured yarn is more complex. There are no yarns ends rather filament has a special shape, its packaging density is quite difficult to measure. Nevertheless, it is sure that its packaging intensity is quite less as compared to compact yarn. Resultantly, texture yarn has higher compressibility coefficient as compared to normal yarn. All these factors contribute to the complexities in measuring fabric thickness.

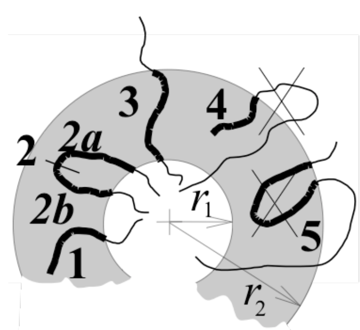

Figure 2-13 Fiber types [67]

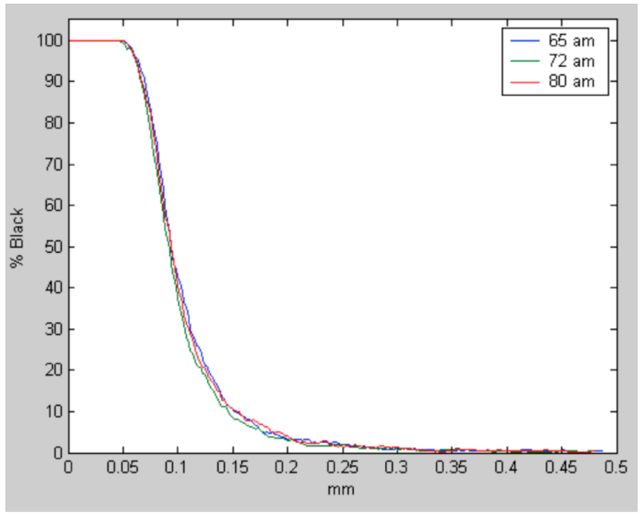

Figure 2-14 Fibre distribution diagram [67]

Our discussion reveals that there is a strong dependence of thermal resistance on fabric thickness. However, we do not agree with the results of Abdel-Rehim et al. [68] that by increasing the thickness, an obvious increase in thermal resistance. It is well conversed by Crow that by increasing density, air gaps will be replaced by polymer which has low thermal resistance. Abdel-Rehim et al. have used the following equation:

$$\lambda \frac{\partial^2 T}{\partial x^2} = \rho C_p \frac{\partial T}{\partial t} + \frac{\partial q_r}{\partial x} \qquad \text{2-45}$$

In this equation they have taken time as a factor, whereas, in steady state condition, it is believed that temperature depends upon distance or thickness of the slab. Nevertheless, authors have presented values of thermal resistance of different fabrics. In our case we have taken thermal resistance only through conduction and have ignored the radiation and heat transfer through convection. It is primarily due to the lack of capacity to measure changes under wet conditions.

Considering these factors, thermal resistance was measured by keeping Alambeta pressure at 1000 Pa. Variation in results shows that settlement of fibres and fabric compressibility have a significant impact on thermal properties. It confirms the work of Bogaty [37] .

Work of Zhu and Li [69] is an exercise to determine the effective thermal conductivity of a porous fabric and they conclude that effective thermal conductivity is a function of pore structure, they call its fractal dimensions of the fabric. They developed a model for the prediction of thermal conductivity. In this model they have ignored the presence of moisture in fabric, whereas, our work is centred on the existence of moisture in the pores of the fabric and its effect on thermal resistance.

2.14 Impact of fibre composition and washing process on air permeability of denim

Air permeability is a considerable factor in the clothing comfort process. It is much dependent on the fibre composition, arrangement of fibres, yarn compactness, porosity and function of textile auxiliaries. Airflow has a fundamental role in the clothing comfort phenomenon. Air permeability is defined by the equation:

$$A = \frac{V}{F\tau(\Delta p)} \qquad \text{2-46}$$

Where:

A- $dm^3m^{-2}s^{-1}$

V - capacity of the flowing medium,

F - the area through which the medium is flowing

τ - time of flow,

Δp - drop in pressure of the medium.

2.15 Moisture management in fabric

Moisture can transfer through fabric in form of vapours and in form of liquid. There are many methods, which are commonly used to measure water vapour permeability. Most common are ASTM E96; ISO 15496; BS 7209; JIS L1099; ISO 2528; ISO 11092 (EN 31092); ASTM 1868. Many studies have compared different methods and finally concluded that there is a significant difference in values. It is difficult to recommend any method. Selection purely depends upon the circumstances and the requirements [70].

Gunesoglu, et al. [71] tested knitted fabrics having different composition of cotton and PET for loop. He came out with a conclusion that fleece made by using polyester-cotton (87:13) for loop has the lowest thermal absorbtivity.

When water is dropped on the surface of any textile material, it moves in multi directions. Its movement depends upon the chemical and physical nature of the textile material. The ability to control the movement of moisture is called moisture management of textile material [61].

Textile materials may be hydrophobic or hydrophilic in nature. Many complexities are attached with the adsorption and absorption processes. Overall, adsorption and absorption of water in textiles create a big change in their thermal characteristics. This change leads to change in their thermal, moisture sensation, and overall comfort properties. There is a strong correlation between moisture management properties of a fabric and its final comfort perception [47, 58, 72-76].

2.16 Friction coefficient and geometrical roughness

Das et al. [77] and Lima et al. [78] describe that fabric friction, which shows the characteristic of fabric related to resistance to motion is taken by the end users as one of the crucial factors in making decision to buy or leave. Sülar and Okur [79] have studied the impact of thickness, stiffness and roughness of the suiting fabric and found that during subjective evaluation, people give importance to these factors.

Sensorial comfort depends upon tactile properties of fabric. KES FB 4 used to test the COF and GR of denim, which are the main contributors of sensorial comfort. Broega et al. have preferred coefficient of friction [80] for the assessment of sensorial comfort. Keeping this factor in view it is obvious from the results that denim made by using Spun PP as weft has the lowest COF along the warp on the side of denim, which touches the human skin. Nevertheless, denim made by using SBC PP has the lowest COF along the weft on backside of denim that touches the human skin.

2.17 Bending rigidity

In this study, we have measured the bending rigidity and the surface roughness. Keeping its importance in view. Moreover, we have added the measurement of friction in our list of objectives. Nevertheless, this study is limited to measure the variation in friction and geometrical roughness of the denim. This variation has been measured by using KES. KES is now a globally admissible system to measure various properties of fabric, which are related to its physical structure. These may be surface profile, bending, thermal comfort, etc. Kawabata developed KES-FB4 to measure the surface friction and surface roughness. KES FB4 can measure precisely fabric mechanical properties. KES has been used to design instruction for programmable sewing machine [81-85].

2.18 Impact of fibre composition and washing process on vapour permeability resistance of denim

Vapour permeability of fabric helps to keep the skin dry under wet condition. Particularly in case of sweating, it plays a significant role. But at the same time, we need fabric, which should provide us shield from strong wind. Moreover, should not help in removing our body heat during winter times. Industry is using membranes to make fabric waterproof and the same time improving its breathing capability.

Following are the main measuring units for water vapour permeability of any fabric [86]:

1. Water vapour permeability [$g\ m^{-2}h^{-1}Pa^{-1}$]
2. Relative water vapour permeability [p%]
3. Water vapour resistance [m^2PaW^{-1}]
4. Water vapour permeability index (-)

In this Study we have used Alambeta to measure water vapour resistance [m^2PaW^{-1}]

2.19 Impact of industrial washing on colour

There is an understood change in color after industrial wash with some chemicals. This change depends upon the type of chemicals being used and the type of fibres present in fabric.

Spectrophotometer (Data Color Spectra flash) using light source D65 and 10° CIE 1976 L*a*b* (CIELAB) equations is commonly used for this purpose. Following equation explains the measuring method.

$$\Delta E^*_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \qquad 2\text{-}47$$

Where:

$L* = 116\, f(Y/Y_n) - 16$

$a* = 500[f(X/Xn) - f(Y/Yn)]$

$b* = 200\,[f(Y/Yn) - f(Z/Zn)]$

If $f(X/X_n)$, $f(Y/Y_n)$ and $f\,(Z/Z_n)$ are taken as $f(I)$
Then $f(I) = I^{1/3}$, for $I > 0.008856$
Otherwise $f(I) = 7.787\, I + 16/116$

Here X, Y, Z and X_n, Y_n, Z_n are the tristimulus values of the sample and a specific reference white considered. It is common to use the tristimulus values of a CIE standard illuminant or a light source for the X_n, Y_n, Z_n values.

In the equation 1:
ΔL*=*the change in lightness*
Δa*= *the change in red-green coordinates*
Δb*=*the change in yellow-blue coordinates*

2.20 Subjective evaluation

Pan et al. [99] have discussed problem attached with KES in measuring hand value. They have proposed subjective evaluation process for better understanding. Subjective evaluation is one part of this whole study. Ozcelik et al. [87] have studied the fabric handle and they derived the conclusion that handle values entirely depend upon the mechanical properties of fabrics. We add that it also depends upon the person who is doing the judgment. Reeiners et al. [88] reinforce our observation. They conducted a study to find out the difference in human perception and established a significant difference among different groups of people.

To improve the objective evaluation of fabrics by means of the instruments, more sensitive and faster working instruments are permanently developed, however, in order to achieve significant correlation with the subjective evaluation or even to replace it. However, profound significance of subjective evaluation cannot be disregarded [89-93].

As concluded by Barker [58], objective and subjective measurements, both are incredible and are capable to serve certain purposes. Although, none of these is fully able to predict the overall comfort, yet testing machine can tell thermal conductivity of any fabric, friction of the fabric surface and many more parameters. An individual can give his or her observation about the skin sensation, warm or cool effect, etc. but they cannot portray overall comfort. The role of cutting, designing and fitting cannot be ignored away as the human body is a combination of unlike shapes and there is a big diversification among women, men, young people, kids and even people living in diverse parts of the globe.

2.20.1 Kendall's concordance w of conventional and functional denim

Kendall's coefficient of concordance [W] is commonly used to measure agreement among the group of observers [94]. Following equations are used to measure the W.

$$W = \frac{12 * SSR}{K^2 n(n^2 - 1)} \qquad \text{2-48}$$

$$SSR = \sum R^2 - \frac{\left(\sum R^2\right)}{n} \qquad \text{2-49}$$

Where:

R is total of row, n means number of items and k is number of sets of ranks.

Kendall Coefficient of concordance *W* indicates the agreement of the experts to evaluate the samples. If k (n-1) *W* is greater than the critical value of chi-square, then one can reject the null hypotheses, which claims that there is no common ranking. One should be careful in finalizing the conclusion because, significant value of W does not show that ranking are true. It only provides the significance, not the validity of degree of association among different ranks [94].

2.20.2 Median and 100 (1-α) confidence interval of conventional and functional denim

Classical method to calculate median for any data has many shortcomings, when it is applied on a grouped or ordinary data having categories. For better calculation few adjustments are required to calculate median of a data, which consists of categories and order. Data has ordinal character they have no metric. In such situation for location estimator, median XM can be used. Following procedure has been proposed in [94]:

$$XM = Me + 0.5 - \frac{F_{Me} - 0.5}{f_{Me}} \qquad 2\text{-}50$$

Where Me is median category which is defined by inequalities:

$$F_{Me-1} \leq 0.5, F_{Me-1} \geq 0.5$$

Where *FMe* is cumulative relative frequency of median category, *fMe* is relative frequency of median category. This characteristic is suitable for the description of mean evaluation of hand or other properties whose evaluation is in ordinal scale.

For some practical purposes the confidence interval of population median *Mp* is more suitable than point estimation *XM*. Computation of 100(1-α) confidence interval of *Mp* consists of following steps. At first two cumulative frequencies (F^*_D, F^*_H) are calculated from relation**:**

$$F_D^*, F_H^* = 0.5 \pm \frac{0.5\mu_{1-\alpha/2}}{\sqrt{n}} \qquad 2\text{-}51$$

The sign + is used for calculation F^*_H and sign – for calculation F^*_D. These frequencies are used for determination of categories D and H. 100(1-α) confidence interval is then given by (D-0.5+d, H-0.5+h), where d and h are corrections.

Analogous to definition of category Me categories D and H are determined by inequalities:

$$D = F_{D-1} \le F_D^*, F_D \ge F_D^* \ and\ H = F_{H-1} \le F_H^*, F_H \ge F_H^* \qquad 2\text{-}52$$

$$d = \frac{F_D^* - F_{D-1}}{f_D} \ and\ h\frac{F_H^* - F_{H-1}}{f_H} \qquad 2\text{-}53$$

2.21 Split-plot analysis

There is a strong dependence of thermal properties of fabric and the textile auxiliaries applied. Study of Tzanov et al. [95] provide enough evidence to establish this link. Amid et al. [96] have studied the impact of finishes on thermal properties and say in their concluding remarks that there is a significant link between the application of finishes and the thermal properties. To test the impact of fibre composition and application of finishes split-plot design was used. Split-plot design is a process in which main plot is considered hard to change and small scale experiments are conducted by dividing the whole plot in sub-plots [97].

2.22 Denim production

This Study strives to develop functional denim able to withstand under diverse climatic conditions. Here is a brief description about the denim manufacturing process.

In the mid 19th century denim was developed which is a most popular fabric of the modern times. Business Wire writes in its report (Jan 9, 2006) that in the year 2004, the value of Jeans market was 49.00 billion US \$ and it is expected that by 2012, it will touch 53.00 billion US \$. The notable point is that world's total apparel exports in 2008 were 361.8 billion US \$ (Word Trade

Organization Data Base). It is quite clear from the facts that alone jeans have one-sixth share of the apparel business in the global market.

Historically, the word 'Denim' originates from French serge de Nîmes. The famous Webster's Dictionary added the word *denim* first time in 1864, where it was referred to fabric made by coarse cotton to make overalls. Denim, also branded as denim fabric,[5] is a very strong and long-lasting twill-woven fabric. Mostly denim is fabricated from cotton, yet polyester and polypropylene are also exercised to fill up yarn. The product is available in multi-colours yet blue is the most common colour to be found everywhere. The warp of denim is dyed while its weft is un-dyed.

Now denim has become the most popular fabric to be widely used to produce various items starting from trousers to skirts. Affecting the culture of modern world, the product has ordinary use in household items and it is swiftly replacing conventional pants that could be utilized by the people of all ages. Across the world, it is becoming popular day by day beyond any cultural, gender or age limitations. Its attractiveness can be judged from the report of Denim and Jean[6] that tells that in 2007, USA imported 273.99 and 249.76 million jeans for men and boys and for women and girls respectively. The report also shows that people prefer jeans made of denim only because it best satisfies their protection and aesthetic needs.

Denim made of cotton is a heavy fabric and it is absorbent. Difficulty arises when the wearer feels ill at ease due to the high amount of moisture accumulated in the fabric as a result of sweating or higher humidity in surrounding. It is mostly due to the changes in thermal parameters of denim when it has a sensitive amount of water in it. One of the possible solutions of this problem is modification in the composition of denim and change in application of textile auxiliaries applied on it during its industrial washing.

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[5] Cotton Incorporated America has used term *"denim fabric"* instead of denim in its technical bulletin ISP 1010. In this report to minimize the ambiguity, we will use "*denim*" to describe twill fabric produced by using dyed warp with course counts.

[6] http://www.denimsandjeans.com/latest-denim-reports/denim-data-figures/report-on-imports-of-denim-jeans-into-usa-in-2007-2008-a-comparison

It can be said that this Study gets inspiration from Kawabata and Niwa [98] who say there is a need to produce engineered garments of higher quality by applying better combinations of fibres and using most modern techniques. They claim that application of technology in garment production is a most powerful tool.

Denim is a thick fabric made by coarse yarn. Its planner weight ranges from 200 to 400 grams per meter square. In most of the cases, open-end yarn is used for some specific reasons. First, it gives better look after doing its washing in shape of garments and second it gives a ring effect, which improves its look. Warp of denim is dyed with vat dyes, most commonly used is Hydron Blue and sulphur black. Some other dyes are also used in washing for colour matching and tinting purposes. Following is a production scheme of denim. Using 100% cotton yarns makes conventional denim. Nevertheless, some people are also using polyester for as weft yarn in denim manufacturing.

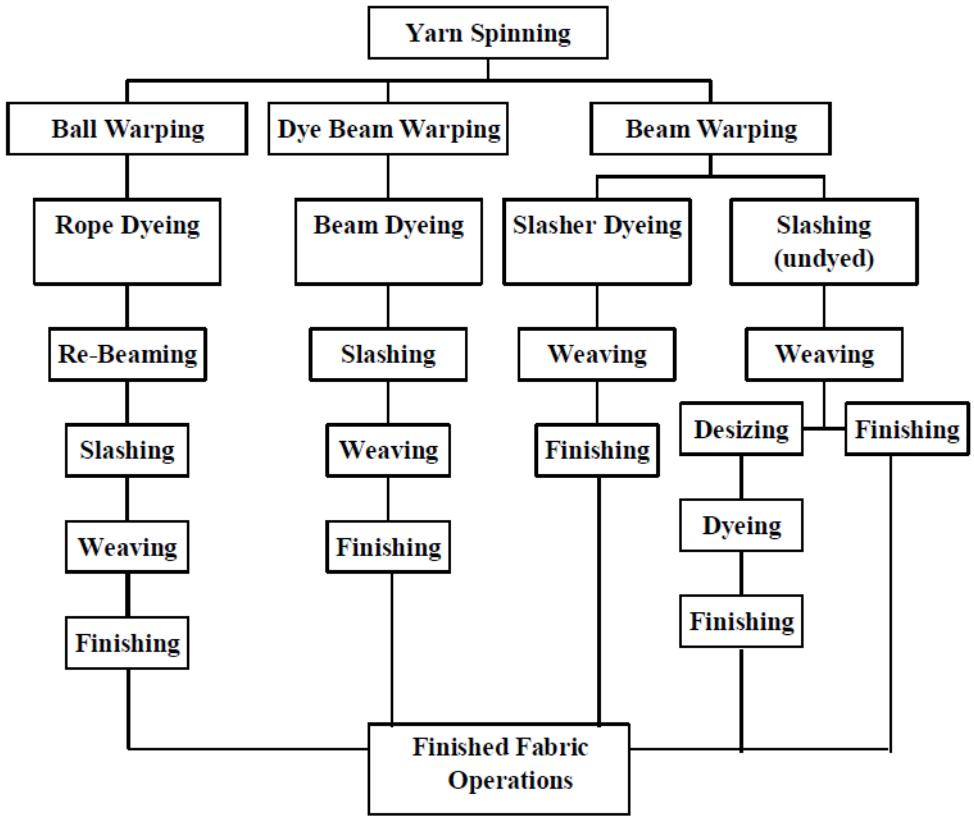

Figure 2-15 Denim manufacturing process [99]

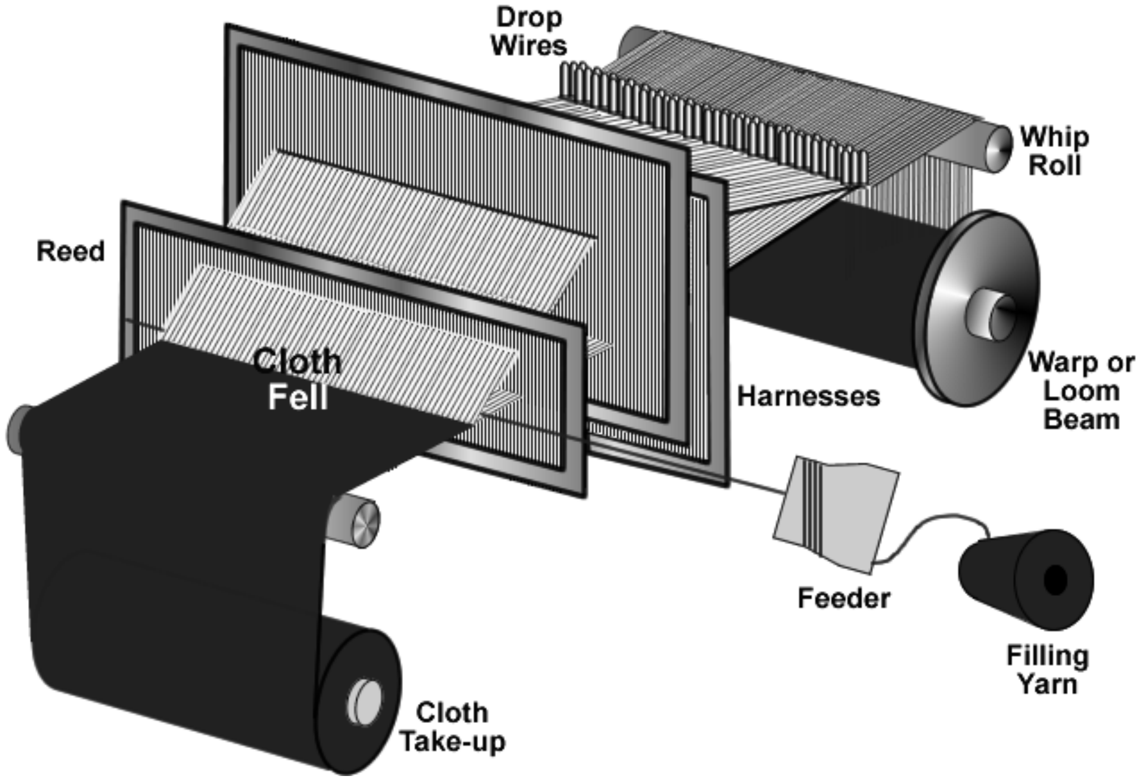

Figure 2-16 Denim manufacturing[99]

2.22.1 Denim and industrial washing

It is quite obvious from any jean shop that jeans made of denim occasionally used in grey form coming from loom. The most common is treatment of denim with some textile auxiliaries after converting it into clothing. Denim washing has a high contribution in its wide acceptance. The most common process is bleaching that have a certain shade, enzymatic treatment for smooth surface and application of softeners for better hand feel. Although, many special textile auxiliaries are also applied [100]. Industrial washing can be used to achieve certain objectives. The most effective is treatment of denim with enzymes[101].

Mazumder [102] has studied the impact of fully biodegradable enzymes in washing and its impact on fabric surface. Change in fabric surface is due to the removal of protruding fibres and this change alters the thermal parameters and leads to change in thermal comfort.

3 Experimental part

Research design contains the following components:

1. Conventional and functional denim samples development
2. Denim samples testing
3. Data analysis

3.1 Manufacturing of conventional and functional denim

One of the objectives of this study is to develop denim suitable under wet conditions. There is a brief description of denim production process in the following paragraphs.

3.1.1 Types of weaves

The most common weave for denim is twill. For this study following three types of twill has been used, considering them most commonly used:

1. Straight Twill 3/1 Z
2. Broken Twill 3/1
3. Herringbone Twill 3/1

Keeping general trend in view, following five denims were produced by using various natural and synthetic yarns as weft and using cotton as warp:

1. Cotton/Cotton
2. Cotton/Spun PP
3. Cotton/AT[7] PP
4. Cotton/SBC[8] PP
5. Cotton/PET[9]

3.2 Denim sample development

Three types of weaves, five types of weft yarn and 12 types of industrial washing processes were used to develop 180 denim samples.

[7] Air Textured Polypropylene
[8] Stuffer Box Crimped Polypropylene
[9] Polyethylene Terephthalate

Here is given the sample specifications. Initially 11 different washings were applied and one sample was kept as untreated. After initial analysis, two samples were dropped due to insignificant difference from others and rest analysis was conducted by using ten washing treatments. In this way total samples available were 150 instead of 180.

Table 3-1 Specifications of denim fabrics used in this study

Description	Denim 1	Denim 2	Denim 3	Denim 4	Denim 5
Warp Yarn	Cotton	Cotton	Cotton	Cotton	Cotton
Warp Tex	49.25	49.25	49.25	49.25	49.25
Warp set [yarns.cm^{-1}]	24.01	24.01	24.01	24.01	24.01
Weft Yarn	Spun PP	[10]SBC PP	[11]AT PP	[12]PET	Cotton
Weft Tex	54.00	38.00	47.78	37.00	49.25
Weft set [yarns.cm^{-1}]	17.71	22.24	20.07	20.86	17.32
Weight after washing[g.m^{-2}]	315	320	328	351	320

3.3 Testing parameters

Following areas were selected for testing and evaluation:

1. Thermal parameters
    a. Thermal conductivity
    b. Thermal absorbtivity
    c. Thermal resistance
2. Air permeability
3. Vapour permeability resistance
4. Colour changes due to washing
5. Moisture management
    a. Moisture absorption rate and time for front and reverse side of denim
    b. Wetted radius of front and reverse side of denim
    c. Front and reverse spreading speed

[10]Stuffer Box Crimped PP
[11]Air Textured PP
[12]Polyethylene Terephthalate

   d. Accumulated one way transport index
   e. Overall moisture management index (OMMC)
6. Kawabata Evaluation System for the testing of:
7. Surface friction
8. Geometrical roughness
9. Warp and Weft Bending Force
10. Subjective evaluation for the testing of:
    a. Warm and cool effect
    b. Softness
    c. Smoothness
    d. Stretch
    e. Bulkiness
    f. Overall comfort

3.3.1 Testing equipment

Following testing instruments have been used for this study:

1. ALAMBETA testing equipment has been used to measure thermal parameters[60].
2. PERMETEST for vapour permeability resistance [103]
3. KES for testing of friction and geometrical roughness of denim
4. Moisture Management Tester (MMT) to test the response of denim when water is dropped on its surface.
5. UNIEG for bending force
6. Air Permeability Tester ATLAS
7. DATA COLOR

3.4 Subjective evaluation

A group of 30 educated people were selected for the subjective evaluation.

3.5 Testing conditions

All tests were carried out in lab where temperature was kept between 20-22 and RH 20-25%.

4 Evaluation of results

4.1 Water and changes in fabric

There are certain changes in fabric structure due to water absorption and adsorption. Following are the results of these tests.

4.1.1 Moisture and density of fabric

The influence of moisture content on cotton fiber density was calculated by using Equation 2.42. Figure 4-1 shows that there is a continuous change in density. It negates the swelling impact. The reason behind this phenomenon is the measurement under pressure. Moreover, gap between the protruding fibres has been filled by water and static charges diminished. Reduction in thickness also contributes in lower thermal resistance at higher humid conditions. We can conclude that porous material may reduce thermal resistance under wet conditions due to the filling of pores with water. Nevertheless, highly porous material provides better resistance under dry condition due to higher resistance of air present in pores and thickness of the fabric.

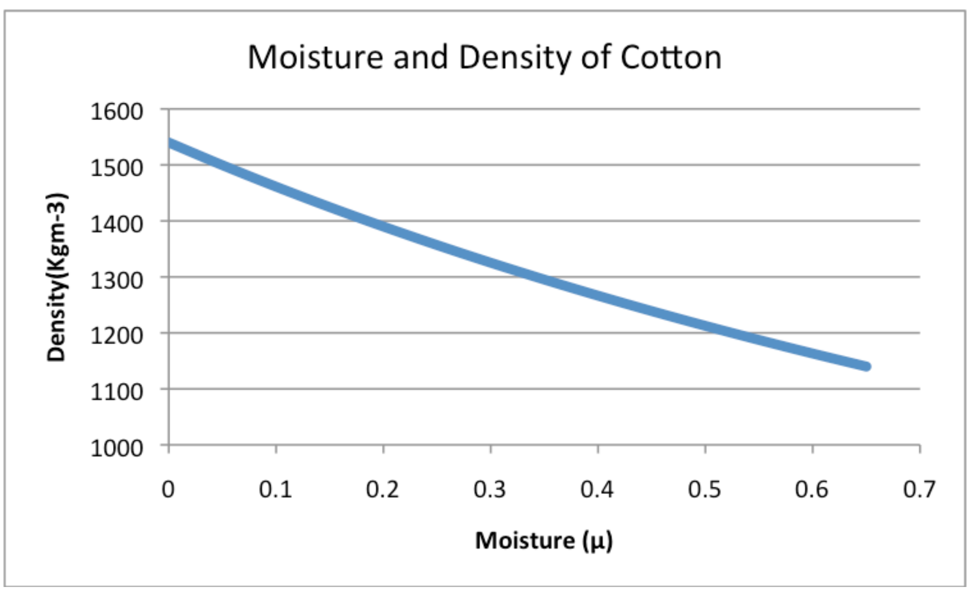

Figure 4-1 Influence of moisture content on density

4.2 Impact of moisture on denim thickness

Moisture present in fabric could be the reason of swelling of natural fibres, particularly cotton. It was observed during testing that wet fabric is compressed more as compared to dry fabric. It may be due to the replacement of air by water molecules, which have reduced the pores and cavities in the fabric. Or it may be due to deletion of static charges among the synthetic fibres. Data shows that there is a continuous and systematic decrease in thickness of denim with the increase of moisture (Figure 4.2 to 4.5).

The ultimate impact of change in thickness will be on the thermal insulation of fabric. Since insulation depends upon the thickness, it shows that change reduction in thermal resistance is not only due to the moisture; it is also due to the change in thickness. It supports the idea that structure is significant for better thermal insulation as compared to the substances or polymers (Figure 4.14 to 4.18).

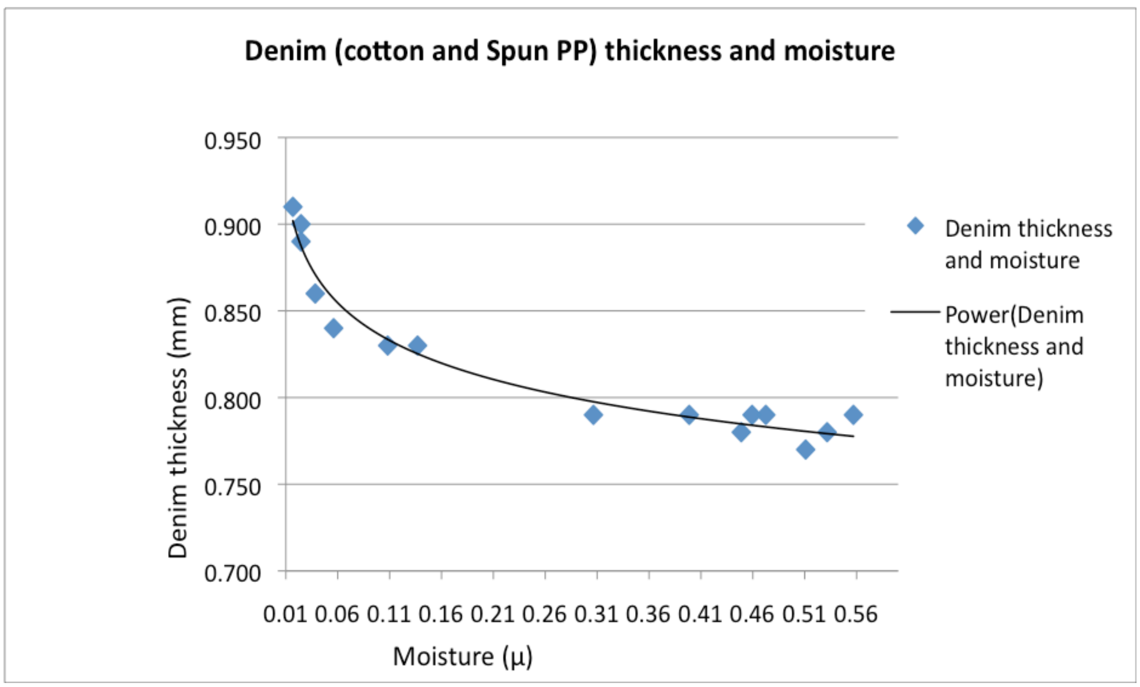

Figure 4-2 Thickness of denim (cotton and spun PP) and moisture (Alambeta at 1000 Pa)

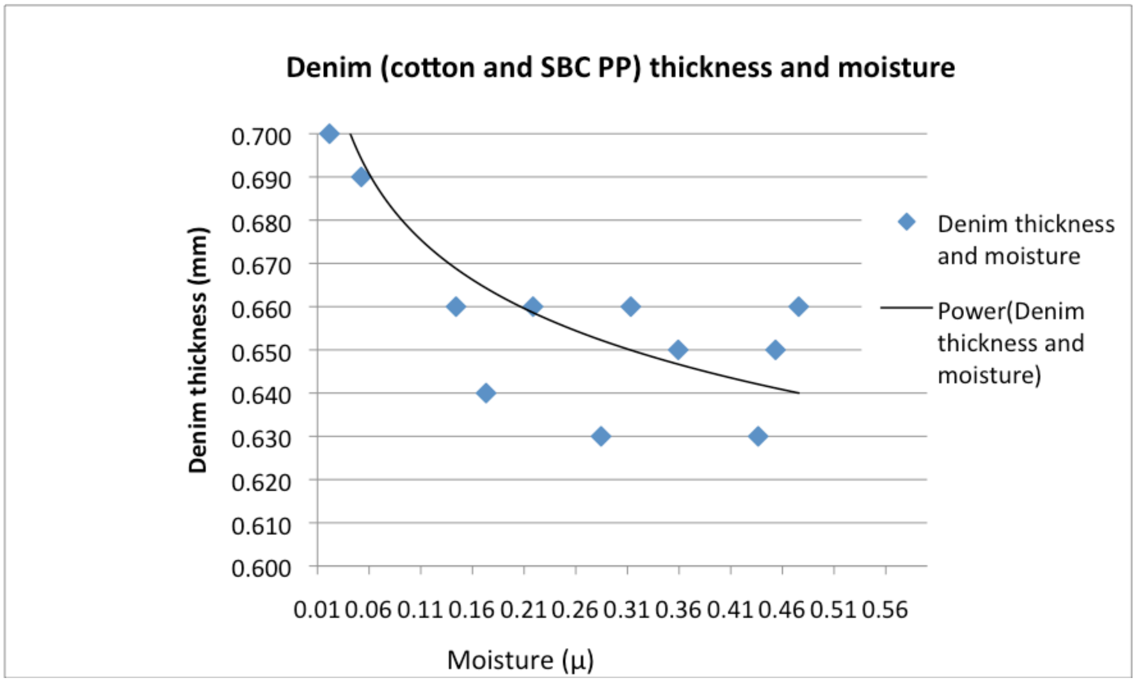

Figure 4-3 Thickness of denim (cotton and SBC PP) and moisture

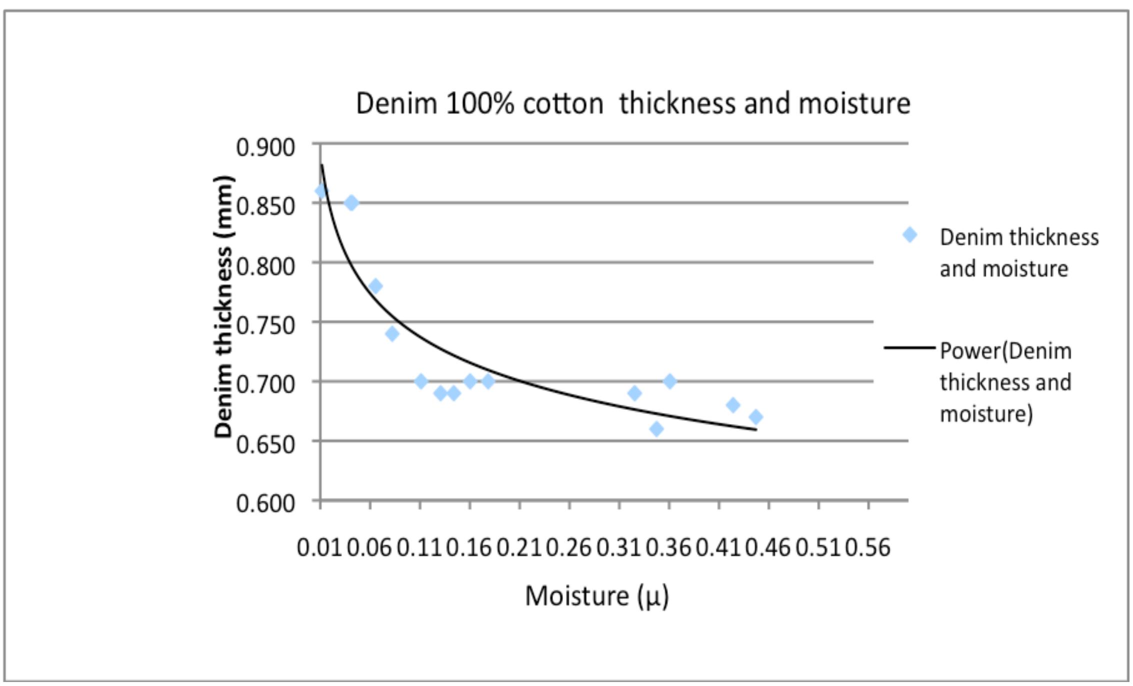

Figure 4-4 Thickness of denim 100% cotton and moisture

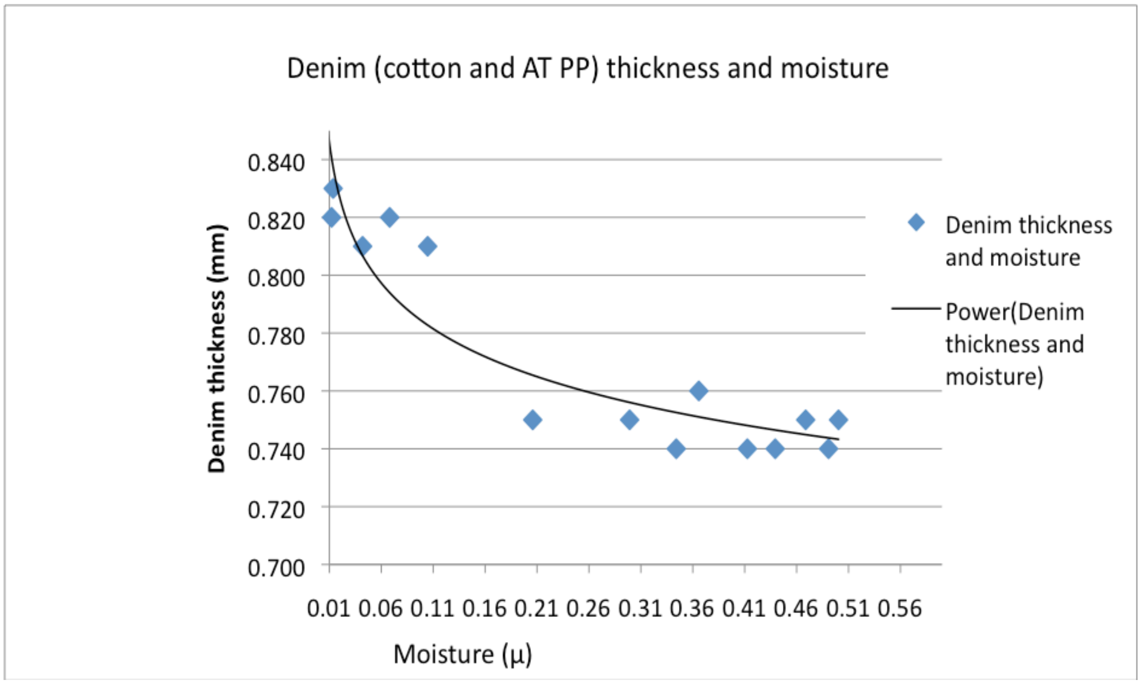

Figure 4-5 Thickness of denim (cotton and AT PP) and moisture

4.3 Moisture and air permeability

Moisture replaces air from the pores of fabric. Pores allow air to pass through the fabric. Air - flow depends upon the space available from the movement of air through fabric. Amorphous region of fabric, which consists of the space between yarns and space between the fibres. Testing proves that denim made of staple fibres has higher air permeability than denim made by filaments (Table 4.1). Moisture fills the air gaps and creates hindrance to flow air through the fabric. It was found during testing that approximately, when the moisture[13] μ goes more than 0.35, air permeability becomes negligible. It shows that there is no airflow from one side to other. Moreover, it is an indicator that all air has been replaced with moisture and now all heat transfer is through polymer and water. At this point all thermal resistance is provided by the water and polymer and role of air is quite negligible. We have observed that there is drastic drop in thermal resistance in the initial stages since major amount of air is replaced during first part of

[13] (wet weight-dry weight)/ (wet weight)

moisture regain. This observation is supported if we see thermal resistance and airflow graph against moisture at the same time.

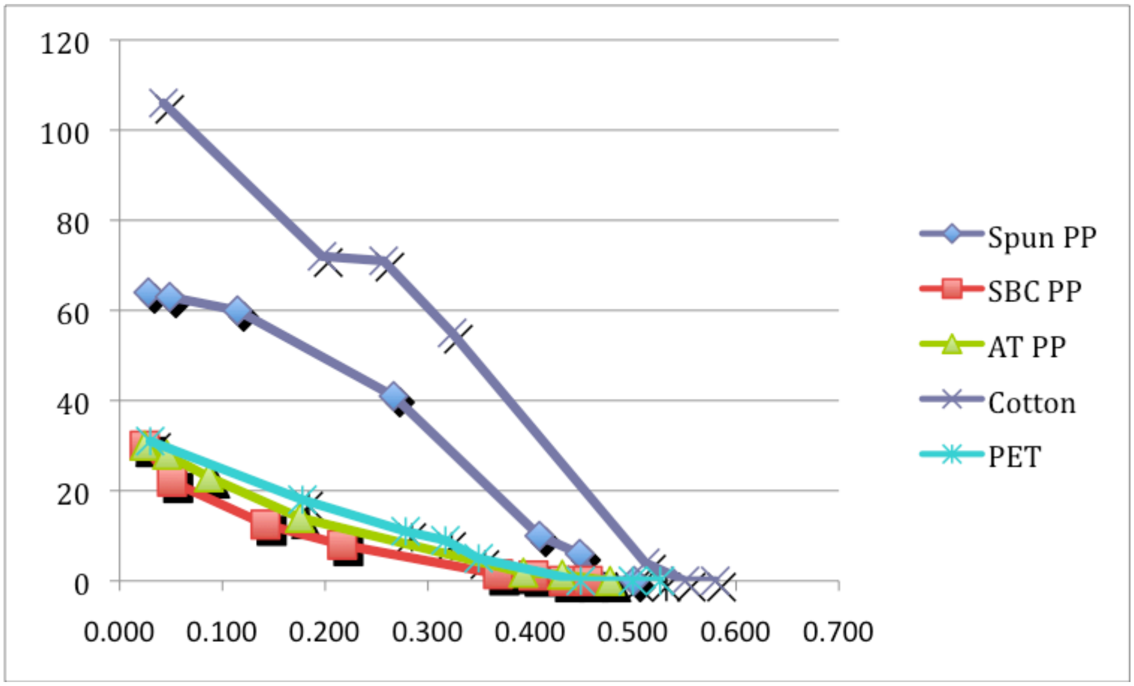

Figure 4-6 Moisture and air permeability

Table 4-1 Air permeability and moisture in denim

Type of weft	Moisture in denim	Air permeability (l $m^{-2}s^{-1}$)	Type of weft	Moisture in denim	Air permeability (l $m^{-2}s^{-1}$)
Spun PP	0.028	64	Cotton	0.043	106
Spun PP	0.049	63	Cotton	0.197	72
Spun PP	0.115	60	Cotton	0.257	71
Spun PP	0.267	41	Cotton	0.324	55
Spun PP	0.409	10	Cotton	0.512	4
Spun PP	0.448	6	Cotton	0.550	0
Spun PP	0.464	0	Cotton	0.580	0
Spun PP	0.501	0	PET	0.030	31

SBC PP	0.024	30	PET	0.178	18
SBC PP	0.051	22	PET	0.278	11
SBC PP	0.142	12.5	PET	0.317	9
SBC PP	0.217	8	PET	0.349	5
SBC PP	0.368	1.5	PET	0.449	0
SBC PP	0.403	1.2	PET	0.499	0
SBC PP	0.432	0	PET	0.526	0
SBC PP	0.456	0	AT PP	0.176	14
AT PP	0.024	30	AT PP	0.393	1.83
AT PP	0.046	28	AT PP	0.431	1.4
AT PP	0.087	23	AT PP	0.477	0

4.3.1 Compressibility and pressure

There is a detail discussion about the hairiness of the yarn. We tested the compressibility of denim samples and found significant variation in sample thickness. It shows the level of compressibility due to the porosity and hairiness. Denim made by using spun and AT polypropylene have highest compressibility, which shows their capacity of compressibility. This characteristic plays a significant role in the thermal parameters and is the reason to provide better thermal resistance under wet conditions (Table 4-2).

Table 4-2 Difference in thickness and porosity due to change in pressure of ALAMBETA

Weft Yarn	Porosity 200 Pa	Porosity 1000 Pa	Difference %	Fabric thickness 200 Pa	Fabric thickness 1000 Pa	Difference %
Spun PP	0.8293	0.7817	5.74	0.00098	0.00076	22.14
SBC PP	0.7852	0.7607	3.12	0.000746	0.00067	9.89
AT PP	0.8302	0.7806	5.97	0.000995	0.00077	22.50
PET	0.8202	0.8005	2.40	0.000833	0.00075	9.96
Cotton	0.8447	0.8192	3.02	0.000850	0.00073	14.12

4.4 Thermal resistance prediction model

Fabric in wet state is composed of polymers, air and water. All have different thermal conductivity. Due to the variation in thermal conductivity, they have different thermal resistance if the thickness is same. In our case thickness of denim is same and all three matters are inside the fabric. Their arrangement is dynamic and cannot be assessed precisely. Nevertheless, the following equations can be used to measure thermal resistance of polymers, air and water.

4.4.1 Thermal resistance of fibres

Fabric may be composed of one type of fibre or it is a combination of different fibres. In case fabric is composed of different fibres, average thermal conductivity can be calculated by using Equation 2.38. In the following equation, we have used ratio of polymers in the total volume of the fabric as discussed in section 2.12.

$$R_f = \frac{h\varepsilon}{\lambda_{wf}} \qquad \text{4-1}$$

4.4.2 Thermal resistance of air layers

Air has thermal conductivity, which is dependent upon the temperature. In our case, we have tested all samples in a controlled environment, where temperature was between 22-24 Celsius. We have used porosity, which is filled by air and water content as a function of presence of air.

$$R_a = \frac{h(1-\varepsilon)}{\lambda_a \mu} \qquad \text{4-2}$$

4.4.3 Thermal resistance of water layers

Water is present in the fabric and its amount varies. It replaces the air and becomes the part of the fabric. The fabric absorbs its major amount and partially it is attached mechanically. Moreover, small amount is present in the pores present in the fabric. Increase amount of water increases thermal conductivity and consequently decreases thermal resistance.

$$R_w = \frac{h(1-\varepsilon)}{\lambda_w \mu} \qquad \text{4-3}$$

Where:

h [m] is average fabric thickness measured with the help of Alambeta, R_f [m^2KW^{-1}] is thermal resistance of fibre, λ_w, λ_a is thermal conductivity of water and air resistance of fibres present in the fabric [$m^{-1}K^{-1}W$] λ_{wf}, is weighted average thermal conductivity of warp and weft, μ - proportion of moisture in fabric, ε-fibre volume ratio, 1-ε –porosity of the fabric.

We do not have any evidence about the arrangement and presence of fibre, moisture and air in the fabric as discussed in section 2.13.4.

1. All resistances are parallel
2. All resistances are in series
3. Air and moisture in parallel and fibre in series

By applying above-mentioned approaches, we could get substantial agreement with the following arrangement:

$$R_{ts} = \frac{h\varepsilon}{\lambda_{wf}} + \frac{h(1-\varepsilon)}{\lambda_a\mu + \lambda_w\mu} \qquad 4\text{-}4$$

This model shows that thermal resistances of air and moisture are in parallel and then it is presumed in series with fibre. By using this simulation Figures 4.8-4.12 have been developed. This equation is purely based on simulation. It is near to impossible to determine the share and location of water and air present in fabric. Moreover, there is a continuous process of evaporation.

4.4.4 Thermal resistance model and its application

In our study our focus is change of thermal resistance of fabric due to water and we do not have different walls. Considering air, water and polymers all in series and all in parallel, we did not find substantial agreement. However considering air and water parallel and then in series with polymers, we found simulated values are much closer to the measured values.

For this model, fabric volume was divided into three different areas and thermal resistance of each area was calculated separately. Thermal resistances of air and moisture areas were added by using electric resistance analogy and then it was assumed in series with thermal resistance of fibres. Results show that more than 70% reduction in thermal resistance happened during moisture range 0.00 to 0.30, which shows that minor amount of moisture in fabric is responsible for the major reduction in thermal resistance. Nevertheless, further increase in moisture has a little effect on thermal resistance. Results of this study confirm the findings of Hes [59] about the changes in thermal conductivity, thermal resistance and thermal absorbtivity.

Results also provide a link with porosity and the thermal resistance. SBC PP has the lowest space available for air and water and at the same time possesses lowest thermal resistance under wet conditions. It proves that higher porosity can help in making clothing warm under wet conditions.

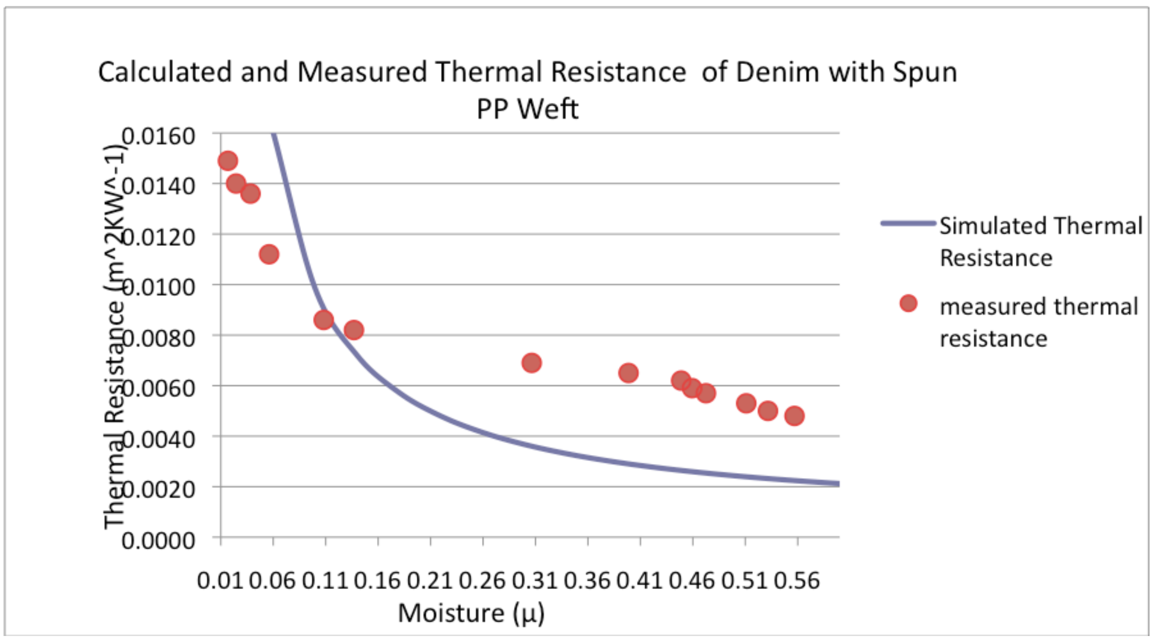

Figure 4-7 Simulated and measured thermal resistance of denim with Spun PP Weft with ALAMBETA, 1000 Pa pressure

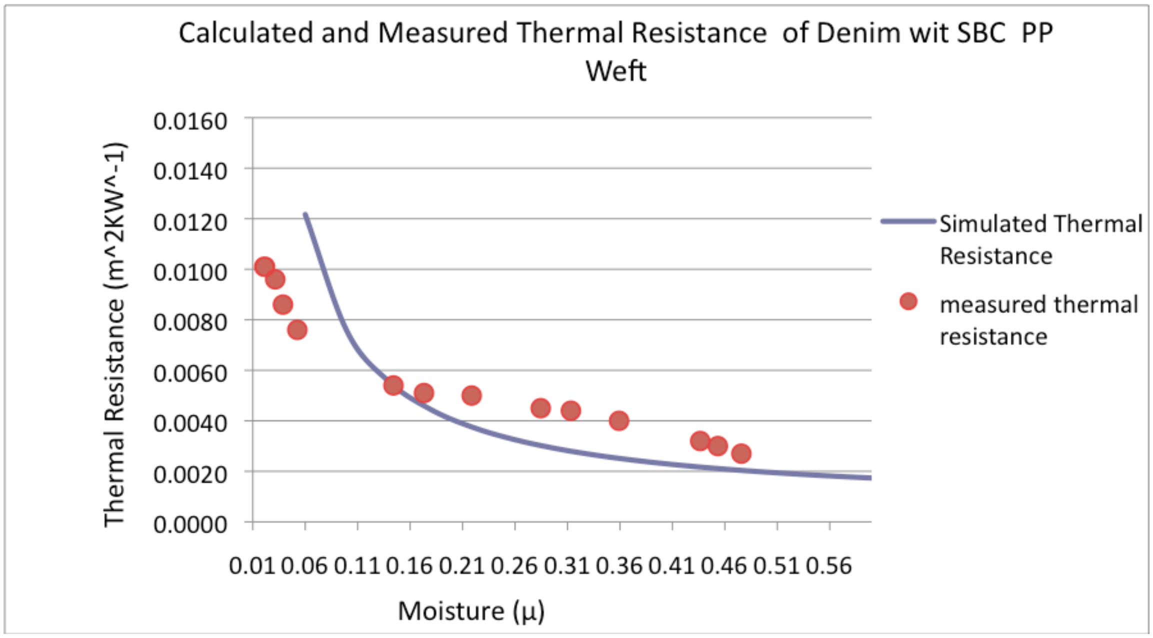

Figure 4-8 Simulated and measured thermal resistance of denim with SBC PP Weft with ALAMBETA, 1000 Pa pressure

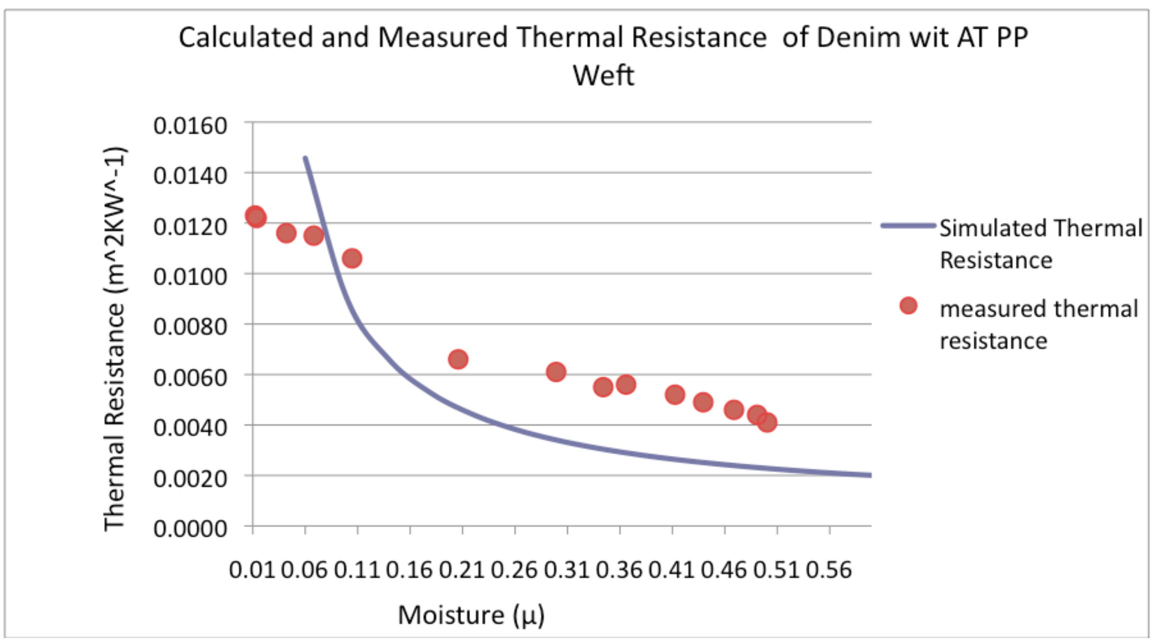

Figure 4-9 Simulated and measured thermal resistance of denim with AT PP Weft with ALAMBETA, 1000 Pa pressure

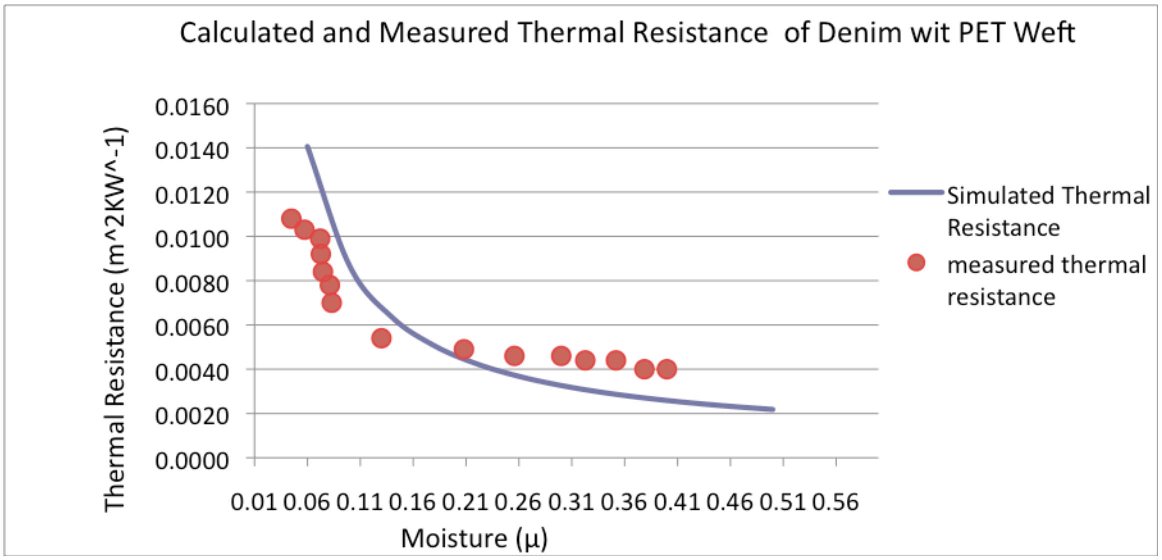

Figure 4-10 Simulated and measured thermal resistance of denim with PET Weft with ALAMBETA, 1000 Pa pressure

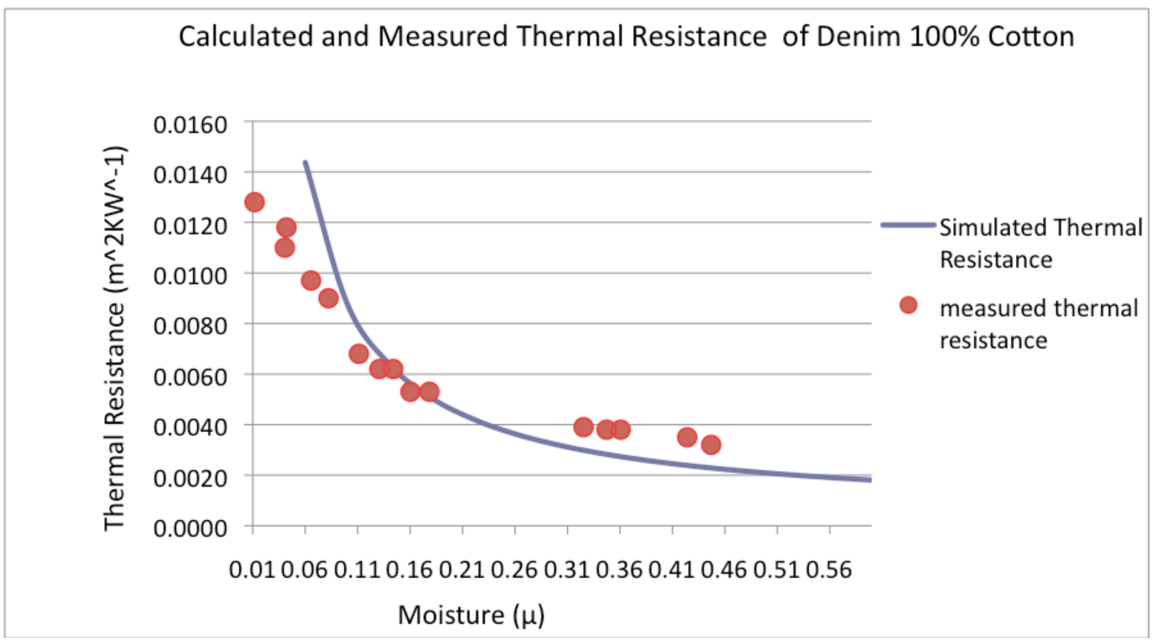

Figure 4-11 Simulated and measured thermal resistance of denim with Cotton Weft with ALAMBETA, 1000 Pa pressure

4.5 Impact of type of weave and thermal parameters

Different types of twill weave are used to make denim. It was presumed that type of weave might have an impact on thermal parameters. To find the actual situation, mean comparison of denims made by using three types of weaves was carried out. Results show that there is no statistically significant variation in thermal parameters (conductivity, absorbtivity and resistance) of different weaves. In all three cases *p* value is greater than 0.05 (Table 4.3). Considering all above discussion it was decided to squeeze the data only to denim made by using 3/1 Z weave, which is quite common. The decision reduced a number of samples from 180 to 60.

Table 4-3 Mean comparison of type of weave and thermal parameters

Description		**Sig.**
Thermal Absorbtivity * Type of Weave	Between Groups	0.15
Thermal Resistance * Type of Weave	Between Groups	0.20
Thermal Conductivity * Type of Weave	Between Groups	0.18

4.6 Impact of fibre composition and industrial washing on thermal parameters

Outcome of the split-plot analysis demonstrates that significance values are less than 0.05 that provide adequate evidence for not accepting the null hypothesis that states that there is no difference in thermal parameters of denim having a different fibre composition and treated with distinct textile auxiliaries.

All above discussion can be concluded on the final note that fibre composition and industrial washing can alter thermal parameters of any fabric. These thermal parameters play a major role in thermophysiological comfort of any fabric. There is a dire need to be careful while selecting textile auxiliaries because industrial washing can create an un-wanted clothing comfort level that may not be chosen by the end users.

ANOVA was also applied to determine the significance of the weft variation and application textile auxiliaries on thermal parameters. Table 4.4-4.6 depict thermal parameters values of denims made by using five different weft yarns and applying 10 distinct textile auxiliaries. Mean comparison (Table 4.7-4.8) shows:

1. Washing of denim has no significant impact on thermal conductivity of denim (*p* value is 0.68).
2. Result shows that there is a drastic change in thermal absorbtivity and thermal resistance due to change in washing (*p* value is less than 0.05).
3. We find that in dry condition, type of weft has no significant impact on thermal conductivity, thermal absorbtivity and thermal resistance, since in all cases *p* value is greater than 0.05.

It is the most important outcome of the study. According to this observation, there is no significant difference in thermal parameters between conventional and functional denim. It proves that functional denim will not provide extra benefit under normal dry condition. In next pages we have done a comparison of changes in thermal parameters under wet condition.

Table 4-4 Thermal conductivity of denim having different weft yarn and industrial washing process [$Wm^{-1}K^{-1}$]

	AT PP	Cotton	Polyester	Spun PP	SBC PP
W1	0.051	0.052	0.052	0.05	0.053
W2	0.051	0.049	0.05	0.049	0.051
W3	0.052	0.052	0.052	0.051	0.053
W4	0.052	0.054	0.054	0.05	0.053
W5	0.052	0.051	0.053	0.05	0.052
W6	0.051	0.052	0.054	0.05	0.053
W7	0.05	0.051	0.052	0.049	0.051
W8	0.052	0.053	0.055	0.05	0.052
W9	0.052	0.051	0.053	0.053	0.052
W10	0.053	0.052	0.049	0.054	0.050

Table 4-5 Thermal absorbtivity of denim having different weft yarn and industrial washing process [$Ws^{1/2}m^{-2}K^{-1}$]

Washing Description	AT PP	Cotton	Polyester	Spun PP	SBC PP
W1	162	143	159	149	152
W2	84	130	152	145	178
W3	153	138	156	144	175
W4	163	147	161	136	168
W5	152	131	145	128	165
W6	157	135	160	138	164
W7	154	139	166	156	148
W8	162	151	156	141	147
W9	157	132	153	150	171
W10	165	137	123	156	178

Table 4-6 Thermal resistance of denim having different weft yarn [m^2KW^{-1}]
(ALAMBETA at 1000 Pa)

	AT PP	Cotton	Polyester	Spun PP	SBC
W1	0.02	0.021	0.018	0.022	0.02
W2	0.02	0.023	0.019	0.023	0.017
W3	0.02	0.021	0.019	0.022	0.016
W4	0.02	0.021	0.018	0.023	0.017
W5	0.021	0.022	0.019	0.023	0.018
W6	0.021	0.022	0.018	0.023	0.017
W7	0.02	0.021	0.018	0.021	0.017
W8	0.018	0.02	0.016	0.022	0.016
W9	0.021	0.023	0.019	0.021	0.017
W10	0.018	0.019	0.023	0.017	0.018

Table 4-7 Mean comparison of thermal parameters of denim samples having different wash by using ANOVA(ALAMBETA at 1000 Pa)

		Sum of Squares	df	Mean Square	F	Sig.
Thermal conductivity	Between Groups	1.86E-05	9	2.06E-06	0.727	0.68
	Within Groups	0.000114	40	2.84E-06		
	Total	0.000132	49			
Thermal absorbtivity	Between Groups	4849.92	9	538.88	2.712	0.01
	Within Groups	7947.2	40	198.68		
	Total	12797.12	49			
Thermal resistance	Between Groups	0.000144	9	1.6E-05	7.592	0.00
	Within Groups	8.44E-05	40	2.11E-06		
	Total	0.000229	49			

Table 4-8 Mean comparison of thermal parameters of denim samples having different weft yarn by using ANOVA(ALAMBETA at 1000 Pa)

		Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Thermal conductivity	Between Groups	1.85E-05	4	4.62E-06	1.83	0.14
	Within Groups	0.000114	45	2.53E-06		
	Total	0.000132	49			
Thermal absorbtivity	Between Groups	500.92	4	125.23	0.46	0.77
	Within Groups	12296.2	45	273.2489		
	Total	12797.12	49			
Thermal resistance	Between Groups	8.48E-06	4	2.12E-06	0.43	0.78
	Within Groups	0.00022	45	4.89E-06		
	Total	0.000229	49			

4.7 Influence of moisture variation on thermal parameters of conventional and functional denim

There is an assumed alteration in thermal parameters of denim due to change in moisture percentage. This part of report investigates the impact of moisture variation on thermal parameters of conventional and functional denim. Thermal parameters of five different denims were tested under various moisture percentages.

We have used different types of equations (polynomial, power, cubic, logarithm, exponential etc) for the best fit or model having minimum standard error. We found that in all three cases, different types of equations give minimum standard error estimate. Keeping it in view we have applied different methods in all three cases. We can derive following derivatives from Figures 4.12-4.14.

1. There is no significant difference in thermal parameters of all denims when the moisture of the dried sample is close to zero. Then, an increase of thermal conductivity and thermal absorbtivity with the increase in moisture percentage is observed. However, the slope of change varies a lot. It is obvious from the figures that cotton and SBC PP have the steepest slope. It shows that thermal conductivity and thermal absorbtivity of denims made by using the cotton and SBC PP increases more as compared to Spun and AT PP. However, PET is in the middle.

2. Increase in thermal absorbtivity brings cool feeling, which creates a discomfort for the wearer. Results exhibit that in the presence of moisture Spun PP and AT PP performs better, or more precisely: they offer relatively dry contact feeling even in the wet state. It means that Spun PP and AT PP can maintain certain level of thermal comfort under extreme conditions.

3. There is relatively slow decrease of thermal resistance of samples made of Spun PP and AT PP under wet conditions, it is evident that these two denims will keep the human body warm and will reduce the heat passage between the body heat and the environment.

4. It was observed, that changes of thermal parameters between 25-90% moisture is slow. It can be concluded that for moisture level above certain limit, there will be no significant change in thermal insulation and thermal contact comfort of the studied denim fabrics.

5. Results show that sample prepared by using SBC PP in weft is among the samples having the lowest thermal resistance. Table 4.2 shows that SBC has the lowest porosity among all samples. It shows that the lower porosity has a significant correlation with the thermal parameters. Higher porosity means presence of higher proportion of air, which has much less thermal conductivity as compared to polymers, and ultimately less volume. These two factors contribute a lot in thermal parameters.

6. Table 4.9 tells the mean values of all selected thermal parameters. It is obvious that Denim made by using Spun PP and AT PP has the higher thermal resistance, lower

thermal absorbtivity. It proves that such denim is more suitable under wet condition and provides better thermal comfort.

From the presented study of thermal comfort properties of denim fabrics in wet state follows, that increase of fabric moisture causes the decrease of thermal resistance of the fabrics and brings cooler thermal contact feeling. Both phenomenon present certain thermal discomfort. It was found, that non – conventional denim fabrics employing cotton as warp and Spun PP or AT PP as weft provides better thermal comfort in wet state to the users, than the conventional denim fabrics.

It is necessary to note, that the observed thermal insulation and thermal contact parameters, both in dry and wet state, were determined for the samples tightly placed between two plates. These plates substantially limited the fabric cooling by evaporation from the fabric surface. The achieved results correspond to the use of the denim fabrics in specific situations, like sitting. Fortunately, sitting is the situation, where the conventional wet trousers might cause very unpleasant thermal contact feelings to their wearer. Thus some of the functional denim fabric described in the paper might present commercially very interesting product for the denim fabric consumers.

Table 4-9 Thermal parameters under dynamic moisture conditions (with Alambeta, 1000 Pa setting)

Weft Yarn	Warp yarn	Moisture in denim [μ]	Thermal Resistance [m^2KW^{-1}]	Thermal Conductivity [$Wm^{-1}K^{-1}$]	Thermal Absorbtivity [$Ws^{1/2}m^{-2}K^{-1}$]	Denim thickness [mm]
Spun PP	Cotton	0.017	0.0149	0.0609	146	0.91
Spun PP	Cotton	0.025	0.014	0.0643	222	0.9
Spun PP	Cotton	0.025	0.014	0.0636	219	0.89
Spun PP	Cotton	0.038	0.0136	0.0632	221	0.86
Spun PP	Cotton	0.056	0.0112	0.0752	321	0.84
Spun PP	Cotton	0.108	0.0086	0.0968	412	0.83
Spun PP	Cotton	0.137	0.0082	0.102	404	0.83
Spun PP	Cotton	0.306	0.0069	0.115	569	0.79
Spun PP	Cotton	0.399	0.0065	0.121	694	0.79
Spun PP	Cotton	0.449	0.0062	0.136	774	0.78
Spun PP	Cotton	0.459	0.0059	0.135	714	0.79
Spun PP	Cotton	0.473	0.0057	0.138	765	0.79
Spun PP	Cotton	0.511	0.0053	0.142	714	0.77
Spun PP	Cotton	0.532	0.005	0.156	801	0.78
Spun PP	Cotton	0.557	0.0048	0.187	992	0.79
SBC PP	Cotton	0.006	0.0105	0.0702	200	0.74
SBC PP	Cotton	0.022	0.0101	0.071	277	0.7
SBC PP	Cotton	0.021	0.0101	0.0735	245	0.74
SBC PP	Cotton	0.031	0.0096	0.0742	313	0.71
SBC PP	Cotton	0.039	0.0086	0.0809	371	0.74
SBC PP	Cotton	0.052	0.0076	0.0905	423	0.69
SBC PP	Cotton	0.144	0.0054	0.121	551	0.66

SBC PP	Cotton	0.173	0.0051	0.125	550	0.64
SBC PP	Cotton	0.219	0.005	0.131	678	0.66
SBC PP	Cotton	0.285	0.0045	0.14	659	0.63
SBC PP	Cotton	0.313	0.0044	0.15	676	0.66
SBC PP	Cotton	0.359	0.004	0.162	671	0.65
SBC PP	Cotton	0.437	0.0032	0.197	856	0.63
SBC PP	Cotton	0.453	0.003	0.212	924	0.65
SBC PP	Cotton	0.476	0.0027	0.241	986	0.66
AT PP	Cotton	0.005	0.0135	0.064	149	0.87
AT PP	Cotton	0.012	0.0123	0.067	245	0.82
AT PP	Cotton	0.014	0.0122	0.068	255	0.83
AT PP	Cotton	0.042	0.0116	0.07	274	0.81
AT PP	Cotton	0.068	0.0115	0.072	292	0.82
AT PP	Cotton	0.105	0.0106	0.076	303	0.81
AT PP	Cotton	0.206	0.0066	0.115	520	0.75
AT PP	Cotton	0.299	0.0061	0.124	689	0.75
AT PP	Cotton	0.344	0.0055	0.134	731	0.74
AT PP	Cotton	0.366	0.0056	0.136	740	0.76
AT PP	Cotton	0.413	0.0052	0.142	821	0.74
AT PP	Cotton	0.439	0.0049	0.151	857	0.74
AT PP	Cotton	0.469	0.0046	0.166	895	0.75
AT PP	Cotton	0.491	0.0044	0.168	910	0.74
AT PP	Cotton	0.500	0.0041	0.182	1000	0.75
Cotton	Cotton	0.012	0.0128	0.067	197	0.86
Cotton	Cotton	0.042	0.0118	0.072	236	0.85

Cotton	Cotton	0.041	0.011	0.074	235	0.85
Cotton	Cotton	0.066	0.0097	0.081	298	0.78
Cotton	Cotton	0.082	0.009	0.083	346	0.74
Cotton	Cotton	0.111	0.0068	0.104	352	0.7
Cotton	Cotton	0.131	0.0062	0.11	384	0.69
Cotton	Cotton	0.144	0.0062	0.111	447	0.69
Cotton	Cotton	0.160	0.0053	0.135	568	0.7
Cotton	Cotton	0.178	0.0053	0.14	579	0.7
Cotton	Cotton	0.325	0.0039	0.176	750	0.69
Cotton	Cotton	0.347	0.0038	0.172	805	0.66
Cotton	Cotton	0.361	0.0038	0.186	845	0.7
Cotton	Cotton	0.424	0.0035	0.194	836	0.68
Cotton	Cotton	0.447	0.0032	0.209	854	0.67
PET	Cotton	0.045	0.0108	0.072	193	0.78
PET	Cotton	0.057	0.0103	0.077	210	0.79
PET	Cotton	0.072	0.0099	0.079	221	0.78
PET	Cotton	0.073	0.0092	0.085	235	0.78
PET	Cotton	0.075	0.0084	0.092	251	0.77
PET	Cotton	0.081	0.0078	0.097	283	0.76
PET	Cotton	0.083	0.007	0.100	282	0.7
PET	Cotton	0.130	0.0054	0.128	288	0.69
PET	Cotton	0.208	0.0049	0.141	319	0.69
PET	Cotton	0.256	0.0046	0.152	391	0.7
PET	Cotton	0.300	0.0046	0.150	580	0.69
PET	Cotton	0.323	0.0044	0.152	638	0.67

PET	Cotton	0.352	0.0044	0.155	688	0.68
PET	Cotton	0.379	0.004	0.168	706	0.67
PET	Cotton	0.400	0.004	0.168	751	0.67

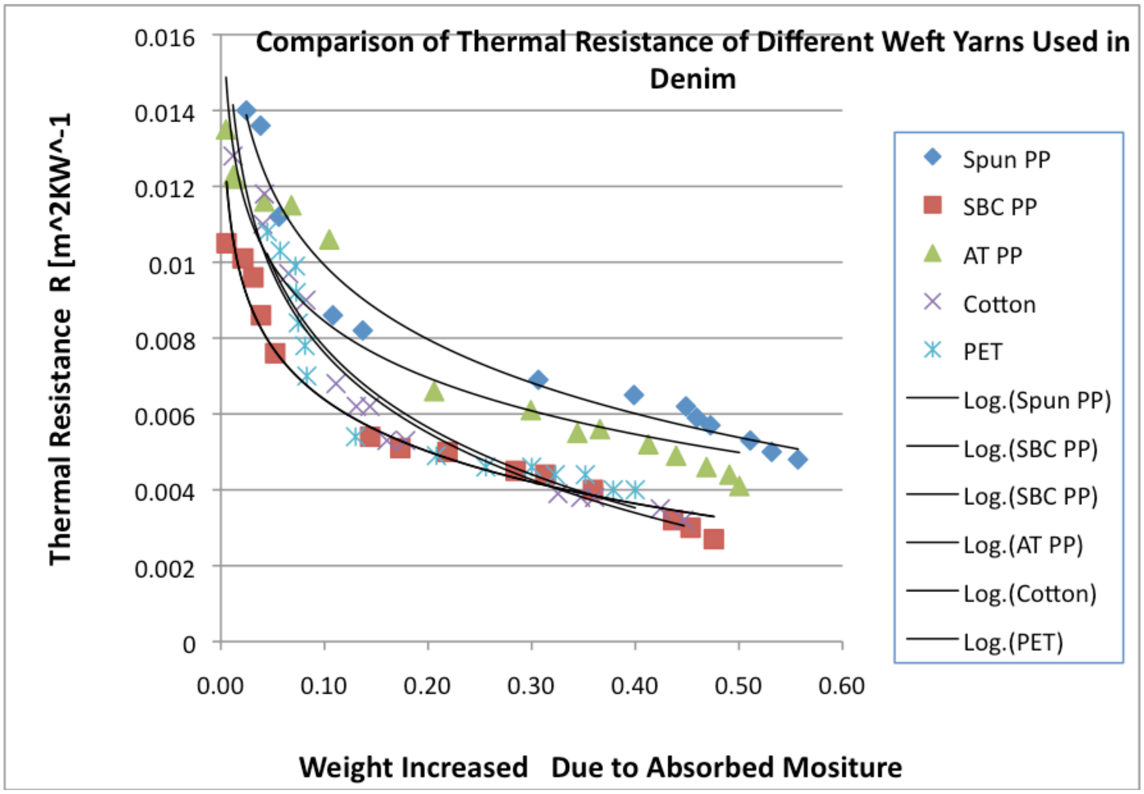

Figure 4-12 Comparison of thermal resistance of different weft yarn used denim under various moisture content (ALAMBETA at 1000 Pa)

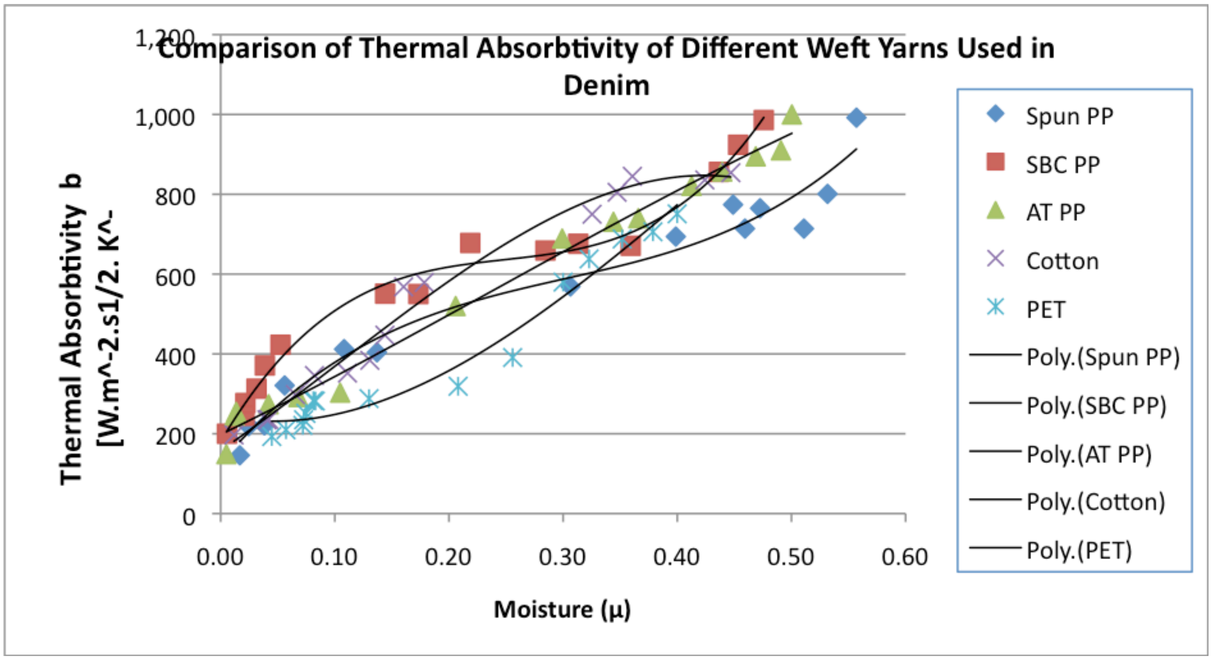

Figure 4-13 Comparison of thermal absorbtivity of different weft yarn used denim under various moisture content (ALAMBETA at 1000 Pa)

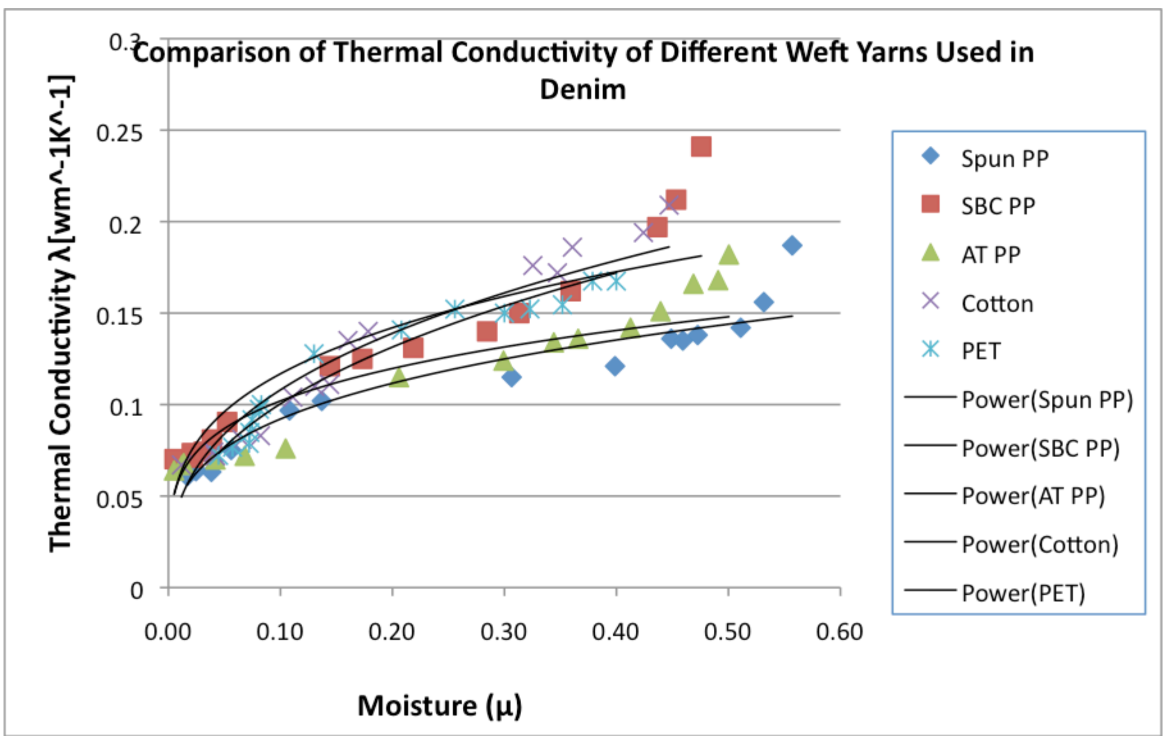

Figure 4-14 Comparison of thermal conductivity of different weft yarn used denim under various moisture content (ALAMBETA at 1000 Pa)

4.8 Impact of different weft materials and washing treatments on moisture management characteristics of denim

We tested denim samples on SDL Atlas Moisture Management Tester according to AATCC Test Method 195-2009. The Moisture Management Tester (MMT) has been developed by Yi Li, Qing Wen Song and Jun Yan Hu to measure the flow of water when drops of water touches the surface of fabric[45]. The instrument gives different indices, which quantify the movement of water in different directions in a textile material. Table 4.10 shows that Overall Moisture Management Capacity (OMMC) of denim made by Spun PP is maximum, which indicates its performance to keep skin dry during wet conditions.

Two-way ANOVA was performed to identify the impact of washing and weft on moisture management parameters. Table 4.11 depicts that in all cases washing has a significant impact on moisture management of fabric. Whereas, type of weft has significant effect in some cases and in some cases it is not. It shows that washing treatment is more important for better moisture management of fabric.

Table 4-10 Moisture management-testing values

Washing	Weft	Wetting Time Top (sec)	Wetting Time Bottom (sec)	Top Absorption Rate (%/sec)	Bottom Absorption Rate (%/sec)	Top Max Wetted Radius (mm)	Bottom Max Wetted Radius (mm)	Top Spreading Speed (mm/sec)	Bottom Spreading Speed)mm/sec)	Accumulative One-way transport Index (%)	OMMC
W1	Spun PP	3.88	3.16	31.00	53.03	20.00	25.00	4.84	5.34	414.43	0.87
W1	SBCPP	4.76	2.99	34.15	49.87	20.00	25.00	4.30	4.79	373.52	0.83
W1	AT PP	4.04	3.80	37.89	38.36	25.00	25.00	4.47	4.22	349.06	0.77
W1	Cotton	4.44	3.08	42.84	43.66	20.00	20.00	4.48	4.46	192.25	0.61
W1	PET	3.48	3.40	30.34	44.93	20.00	20.00	3.36	3.48	280.95	0.67
W2	Spun PP	2.59	2.59	22.98	48.90	25.00	25.00	5.32	6.03	348.92	0.80
W2	SBCPP	3.40	3.40	51.40	43.68	20.00	25.00	4.28	5.31	339.36	0.78
W2	AT PP	3.96	2.83	26.64	42.56	25.00	25.00	4.81	5.29	351.64	0.79
W2	Cotton	2.83	2.67	28.27	38.68	20.00	20.00	4.95	4.98	214.67	0.62
W2	PET	3.96	3.32	24.14	35.55	15.00	20.00	3.05	4.05	265.70	0.67
W3	Spun PP	6.76	4.60	34.35	53.50	30.00	30.00	4.36	5.04	423.36	0.87

W3	SBCPP	6.99	5.00	60.09	49.22	20.00	30.00	3.51	4.53	455.39	0.86
W3	AT PP	9.23	9.47	53.14	41.89	25.00	30.00	2.58	3.17	420.19	0.77
W3	Cotton	10.76	10.19	39.43	62.57	25.00	25.00	1.88	2.14	58.33	0.36
W3	PET	4.70	4.77	56.07	57.78	20.00	25.00	3.10	3.01	230.77	0.61
W4	Spun PP	9.23	16.59	52.12	163.76	5.00	5.00	0.53	0.30	62.92	0.38
W4	SBCPP	7.87	59.96	61.98	50.87	5.00	5.00	0.62	0.08	-253.74	0.11
W4	AT PP	7.63	118.35	58.09	2.90	5.00	5.00	0.64	0.04	-832.98	0.00
W4	Cotton	8.27	15.23	62.64	93.25	5.00	5.00	0.59	0.32	-209.13	0.23
W4	PET	6.76	105.95	30.57	12.99	5.00	5.00	0.72	0.05	-724.82	0.01
W5	Spun PP	9.87	18.52	56.94	33.33	15.00	15.00	0.73	0.50	597.83	0.56
W5	SBCPP	7.55	6.04	57.57	48.92	25.00	25.00	3.30	3.66	423.92	0.83
W5	AT PP	7.55	9.15	51.22	33.81	25.00	30.00	1.57	1.90	435.03	0.64
W5	Cotton	5.80	64.51	53.45	6.20	5.00	5.00	0.84	0.08	-917.74	0.00
W5	PET	7.55	18.60	56.27	31.56	5.00	10.00	0.65	0.41	378.67	0.54
W6	Spun PP	11.00	7.47	46.51	76.12	25.00	25.00	2.63	4.27	314.02	0.84
W6	SBCPP	6.04	5.88	57.39	43.10	25.00	30.00	3.54	4.85	230.53	0.65
W6	AT PP	7.07	7.15	61.61	54.23	25.00	25.00	4.10	4.80	205.43	0.66
W6	Cotton	8.67	8.19	57.17	54.46	15.00	20.00	2.03	2.90	69.29	0.41
W6	PET	6.99	6.76	68.62	48.41	25.00	30.00	3.81	5.00	119.09	0.54
W7	Spun PP	6.52	18.44	77.30	26.66	5.00	5.00	0.75	0.27	-44.99	0.05
W7	SBCPP	6.83	119.95	50.60	0.00	5.00	0.00	0.72	0.00	-833.10	0.00
W7	AT PP	8.43	17.07	68.31	151.58	5.00	5.00	0.58	0.29	195.36	0.52
W7	Cotton	6.04	85.55	62.34	46.28	5.00	5.00	0.81	0.06	-690.01	0.10
W7	PET	7.95	58.19	57.42	36.93	10.00	5.00	0.72	0.09	-414.62	0.07
W8	Spun PP	8.35	4.68	38.96	50.57	25.00	30.00	3.62	4.58	528.71	0.86
W8	SBCPP	7.07	5.00	56.91	47.99	25.00	30.00	3.85	5.51	404.31	0.86
W8	AT PP	11.00	6.20	48.93	25.73	25.00	30.00	2.10	3.19	320.27	0.64
W8	Cotton	14.27	11.56	34.87	157.83	30.00	30.00	2.36	3.71	308.16	0.87
W8	PET	7.55	0.11	53.79	47.23	25.00	30.00	3.46	4.92	308.94	0.75
W9	Spun PP	7.31	119.95	51.24	0.00	5.00	0.00	0.67	0.00	-820.76	0.00
W9	SBCPP	7.47	119.92	55.02	0.00	5.00	0.00	0.66	0.00	-764.86	0.00
W9	AT PP	7.07	119.95	51.27	0.00	5.00	0.00	0.69	0.00	-767.90	0.00
W9	Cotton	6.33	119.95	69.79	0.00	5.00	0.00	0.77	0.00	-811.46	0.00
W9	PET	5.40	119.95	71.26	0.00	5.00	0.00	0.90	0.00	-815.90	0.00
W10	Spun PP	43.47	8.27	7.81	117.65	10.00	15.00	0.23	0.74	908.75	0.75
W10	SBCPP	11.08	9.63	35.30	30.34	20.00	20.00	1.35	1.41	237.74	0.41
W10	AT PP	16.35	12.36	68.22	92.35	10.00	10.00	0.37	0.46	522.93	0.73
W10	Cotton	10.76	13.16	57.07	92.45	5.00	5.00	0.46	0.38	264.84	0.58
W10	PET	8.19	19.88	57.78	34.01	10.00	10.00	0.65	0.32	124.70	0.26

Table 4-11 Two-way ANOVA for effect of type of washing treatments and weft yarns on fabric wetting time

	Source	DF	SS	MS	F	P
Top Wetting Time (WTt)	Type of Washing Treatment	9	707.14	78.5714	3.47	0.004
	Type of Weft Yarn	4	127.44	31.8604	1.41	0.251
	Error	36	815.11	22.6419		
	Total	49	1649.69			
		R-sq = 50.59%				
Bottom Wetting Time (WTb)	Type of Washing Treatment	9	67671.3	7519.04	14.82	0.000
	Type of Weft Yarn	4	1336.0	333.99	0.66	0.625
	Error	36	18262.1	507.28		
	Total	49	87269.3			
		R-sq = 79.06%				

Table 4-12 Two-way ANOVA for effect of type of washing treatments and weft yarns on maximum wetted radii of the fabric

	Source	DF	SS	MS	F	P
Top Maximum Wetted Radius (MWRt)	Type of Washing Treatment	9	3150.5	350.056	18.89	0.000
	Type of Weft Yarn	4	133.0	33.250	1.79	0.151
	Error	36	667.0	18.528		
	Total	49	3950.5			
		R-sq = 83.12%				
Bottom Maximum Wetted Radius (MWRb)	Type of Washing Treatment	9	5348	594.222	40.21	0.000
	Type of Weft Yarn	4	208	52.000	3.52	0.016
	Error	36	538	14.778		
	Total	49	6088			
		R-sq = 91.26%				

Table 4-13 Two-way ANOVA for effect of type of washing treatments and weft yarns on water spreading speed

	Source	DF	SS	MS	F	P
Top Spreading Speed (SSt)	Type of Washing Treatment	9	110.705	12.3006	27.37	0.000
	Type of Weft Yarn	4	3.005	0.7514	1.67	0.178
	Error	36	16.178	0.4494		
	Total	49	129.888			
		R-sq = 87.55%				
Bottom Spreading Speed (SSb)	Type of Washing Treatment	9	204.795	22.7550	45.84	0.000
	Type of Weft Yarn	4	7.906	1.9764	3.98	0.009
	Error	36	17.872	0.4964		
	Total	49	230.573			
		R-sq = 92.25%				

Table 4-14 Two-way ANOVA for effect of type of washing treatments and weft yarns on accumulative one-way transport

Source	DF	SS	MS	F	P
Type of Washing Treatment	9	7797893	866433	12.62	0.000
Type of Weft Yarn	4	1011407	252852	3.68	0.013
Error	36	2470908	68636		
Total	49	11280208			

Table 4-15 Two-way ANOVA for effect of type of washing treatments and weft yarns on OMMC

Source	DF	SS	MS	F	P
Type of Washing Treatment	9	3.78827	0.420919	17.25	0.000
Type of Weft Yarn	4	0.35303	0.088258	3.62	0.014
Error	36	0.87834	0.024398		
Total	49	5.0164			

4.9 Sensorial comfort appraisal of denim by objective assessment of surface mechanical characteristics

Table 4.16-4.19 provides enough information to conclude that there is a mix picture. It is quite difficult to derive any solid conclusion about the coefficient of friction and geometrical roughness of denim made by using distinct yarns in the weft. All denim samples were tested in warp and weft direction. Furthermore, samples were also tested from topside and backside and every test was conducted nine times. Tests having significant variation were dropped. Means of the values were compared. Following conclusion can be derived from all testing:

[1] COF Warp Backside.

Denim made by using spun PP has the lowest COF (0.192) in warp direct on the backside, whereas, AT PP has the highest value (0.216) and cotton is in middle (0.208). It shows that spun PP creates minimum friction due to staple structure. This outcome is much important for denim manufacturers who are willing to use spun PP as a weft yarn in manufacturing denim.

[2] GR Warp Backside.

Denim made by using cotton as warp and weft yarn have the lowest value of GR (2.787 µm) in warp direction on the backside of denim. Whereas, spun PP has the highest value (6.763 µm) and PET is second to it (6.73 µm). Moreover, AT PP and SBC PP are in the middle (4.353 µm and 3.631 µm respectively). This huge difference is mainly due to the staple and filament nature of these yarns.

[3] COF Weft Backside.

SBC PP has the lowest values of COF (0.151) in weft direction on the backside, whereas, PET has the highest value (0.204). Spun PP, cotton and AT PP are in the middle. It indicates that denim by using PET as weft yarn has minimum alignment along the x-axis. It may be due to the high texture and high number of crimps as compared to SBC PP.

[4] GR Weft Backside.

SBC PP has the lowest value of GR (2.895 µm) in weft direction on the backside of denim. Whereas, denim made by using cotton as weft yarn has the highest value (4.318 µm) and SBC PP is at the lowest position (2.895) µm). Furthermore, spun PP, PET and AT PP are in the middle (3.751 µm, 4.014 µm, and 3.317 µm, respectively).

[5] COF Warp Face side

Denim made by using the SBC PP has the lowest COF (0.172) in warp direction on the topside, whereas, spun PP and cotton have the higher values (0.192 and 0.190 respectively). It shows that spun PP and cotton have maximum friction due to staple structure. It is significant to note that denim samples have same warp, which covers more than 75% area of topside. There is the only variation in weft yarns, which covers more than 75% area of the backside of denim.

[6] GR Warp Face side

PET has the lowest value of GR (2.843 µm), whereas, SBC PP has the highest value (3.816 µm) on the topside in warp direction.

[7] COF Weft Topside

SBC PP has the lowest value of COF (0.184) on the face side along the weft. It may be due to the more alignment of the filament. Table 4.19 also tells that spun PP, cotton and PET have the higher values of COF. It may be concluded that staple fibres have more friction as compared to filament.

[8] GR Weft Topside

Denim made by using this has the highest value of GR (10.215 µm) in warp direction on the topside of denim, whereas, PET has the lowest value (6.375 µm). All the rest three denims made by using spun PP, AT PP and SBC PP are in the middle (7.670 µm, 7.936 µm, and 6.678 µm respectively).

All above discussion provides enough information to conclude that there is a mix picture. It is quite difficult to derive any solid conclusion about the COF and GR of denim made by using distinct yarns in the weft.

Sensorial comfort depends upon tactile properties of fabric. KES FB 4 used to test the COF and GR of denim, which are the main contributors of sensorial comfort. Keeping this factor in view it is obvious from the results that denim made by using Spun PP as weft has the lowest COF along the warp on the side of denim, which touches the human skin. Nevertheless, denim made by using SBC PP has the lowest COF along the weft on backside of denim that touches the human skin.

Table 4-16 COF and GR of Warp and Backside

	Coefficient of Friction Warp and Backside [-]			Geometrical Roughness Warp and Backside [µm]		
Type of Weft yarn	µ	σ	CV %)	µ	σ	CV %)
Spun PP	0.192	0.0060	3.610	6.763	1.065	15.750
SBC PP	0.196	0.0116	5.940	3.631	0.634	17.440
AT PP	0.216	0.011	5.220	4.353	0.634	14.579
PET	0.204	0.007	3.311	6.735	0.744	11.050
Cotton	0.208	0.014	6.872	2.787	0.211	7.590

Table 4-17 COF and GR of Weft and Backside

	Coefficient of Friction Weft and Backside [-]			Geometrical Roughness Weft and Backside [µm]		
Type of Weft yarn	µ	σ	CV %)	µ	σ	CV %)
Spun PP	0.199	0.0060	3.190	3.751	0.396	10.562
SBC PP	0.151	0.0080	5.280	2.895	0.266	9.219
AT PP	0.201	0.011	5.509	3.317	0.241	7.278
PET	0.204	0.007	3.210	4.014	0.584	14.540
Cotton	0.161	0.008	4.900	4.318	0.408	9.450

Table 4-18. COF and GR of Warp and Face side

	Coefficient of Friction Warp and Face side [-]			**Geometrical Roughness Warp and Face side [µm]**		
Type of Weft yarn	µ	σ	CV %)	µ	σ	CV %)
Spun PP	0.192	0.0078	4.079	3.064	0.311	10.140
SBC PP	0.172	0.0194	11.258	3.816	0.447	11.720
AT PP	0.181	0.008	4.200	3.124	0.345	11.049
PET	0.180	0.007	3.550	2.843	0.275	9.680
Cotton	0.190	0.011	6.949	3.324	0.505	15.205

Table 4-19. COF and GR of Weft and Face side

	Coefficient of Friction Weft and Topside [-]			**Geometrical Roughness Weft and Topside [µm]**		
Type of Weft yarn	µ	σ	CV %)	µ	σ	CV %)
Spun PP	0.203	0.0089	4.380	7.670	0.960	12.510
SBC PP	0.184	0.0120	6.330	6.688	2.946	34.308
AT PP	0.193	0.007	3.400	7.936	0.550	6.930
PET	0.201	0.008	3.820	6.375	1.153	18.088
Cotton	0.197	0.011	5.748	10.215	0.678	6.646

4.10 Impact of fibre composition and washing process on air permeability of denim

Air permeability of denim samples were tested by using Equation 2.46 as discussed in section 2.14. Table 4.20 shows that there is a significant variation among different denim samples. Denim made by cotton and Spun PP has the highest airflow it is mainly due to the staple fibres used to make these yarns. Nevertheless, industrial washing process has no set pattern. Results show that staple fibre provides better flow of air that has a fundamental role in the clothing comfort phenomenon.

Table 4-20 Air Permeability of denim having different weft yarn and industrial washing process [$l\ m^{-2}s^{-1}$]

	AT PP	Cotton	PET	Spun PP	SBC PP
W1	75	190	63	166	67
W2	65	196	65	155	63
W3	68	197	67	139	61
W4	66	179	58	145	64
W5	69	209	65	162	65
W6	60	156	45	121	48
W7	66	175	60	138	55
W8	64	179	61	148	62
W9	60	179	58	131	60
W10	65	210	67	157	80

4.11 Impact of fibre composition and washing process on vapour permeability resistance of denim

Vapour permeability of fabric helps to keep the skin dry under wet condition, particularly in case of sweating. In this study we have measured the water vapour resistance. These tests were carried on Computer Evaluated Permetest Skin Model developed by Sensora Instruments Czech Republic. This instrument is based on the ISO 11092 method. Apparently, there is no set pattern in the response of different denims. We find a scattered picture, which indicates many factors that contribute to the vapour permeability. Nevertheless, denim made by cotton has lesser vapour permeability resistance (Table 4.21).

Table 4-21 Water vapour permeability resistance of denim having different weft yarn $[m^2\,PaW^{-1}]$

	AT PP	Cotton	PET	Spun PP	SBC PP
W1	7.3	4.4	4.9	6.9	6.4
W2	7.3	4.5	4.7	6.6	4.8
W4	6.9	6.5	10.2	6.4	6.1
W5	8.3	5.9	5.5	8	7.6
W6	8.7	7.9	7.2	6.5	6.9
W7	6.3	5.3	5.2	6	5.8
W8	7	5.6	4.9	6.8	5.4
W9	6.5	4.9	6.5	4.6	5.2
W9	6.3	5.1	4.5	5.6	5.7
W10	6.6	5.3	6.4	5	5.2

4.12 Bending rigidity

Bending force represents the bending rigidity of any material discussed in section 2.17. Table 4.22 tells about the bending force of different denims. It is obvious from the table that in both cases (warp and weft) Spun PP has the lowest bending force, which means that it creates less hindrance in the movement of body.

Table 4-22 Bending force warp and weft

S_N0	Warp Yarn	Weft Yarn/Filament	Bending Force Warp [mN]	Bending Force Weft [mN]
1	Cotton	Spun PP	45.90	22.00
2	Cotton	Spun PP	46.90	20.00
3	Cotton	Spun PP	51.30	22.90
4	Cotton	SBC PP	58.50	24.40
5	Cotton	SBC PP	60.40	25.50
6	Cotton	SBC PP	63.00	28.20
7	Cotton	AT PP	63.60	29.00
8	Cotton	AT PP	64.70	30.20
9	Cotton	AT PP	63.10	29.00
10	Cotton	Cotton	63.50	30.20
11	Cotton	Cotton	62.20	28.50
12	Cotton	Cotton	65.70	29.70
13	Cotton	PET	65.50	28.00
14	Cotton	PET	68.30	28.50
15	Cotton	PET	68.30	28.50

4.13 Impact of industrial washing on colour

Table 4.23 consist of values of the colour difference between washed and unwashed denim fabric specimens. Following conclusion can be derived from Table 4.23:

1. There is a significant change in the colour from the standard in all cases.
2. There is a high correlation between functional and conventional denim in L* (0.99) and b* (0.96) and E (0.93). However, in case of a*, correlation is not strong (0.37).
3. Table 4-24 depicts that there is a drastic change in Δ E when the sample is desized and treated with enzymes. Nevertheless, this change is significant when the sample is bleached.
4. In most of the cases the trend of change is similar. Only difference is in intensity of change.

Table 4-23 Colour Measurement

Washing Ref	**Washing Detail**	**Functional Denim**	**ΔL***	**Δa***	**Δb***	**ΔE**	**Conventional Denim**	**ΔL***	**Δa***	**Δb***	**ΔE**
W1	Desized and rinsed	1PP	-1.44	0.01	0.22	1.45	1COT	-2.79	0.60	-1.54	3.24
W2	Desized and treated with enzymes	2PP	-1.17	-0.09	0.24	1.20	2COT	-2.38	0.48	-1.67	2.95
W3	Desized,,treated with enzymes and bleached	3PP	7.39	0.15	3.67	8.25	3COT	6.07	0.39	2.47	6.57
W4	Desized, bleached and applied silicone softener	4PP	10.50	0.25	6.10	12.14	4COT	7.42	0.76	4.60	8.76
W5	Desized and bleached	5PP	4.11	0.42	3.07	5.15	5COT	2.02	0.55	2.07	2.94
W6	Desized, bleached and applied quick dry auxiliary	6PP	5.02	0.34	4.16	6.53	6COT	1.97	0.46	2.46	3.19
W7	Desized, bleached and applied cationic softener	7PP	6.90	0.44	3.59	7.79	7COT	5.52	0.44	2.46	6.06
W8	Desized, enzyme and stone washed	8PP	-0.40	-0.05	-0.05	0.41	8COT	-2.94	0.06	-0.44	2.97
W9	Desized, bleached, enzyme and stone washed	9PP	14.89	0.29	5.86	16.00	9COT	11.34	0.66	4.50	12.22
W10	Desized, bleached and application of water repellant auxiliary	10PP	4.87	0.47	3.32	5.91	10COT	3.29	0.53	2.27	4.03
W11	Desized, rinsed and peached	11PP	-1.21	0.16	-0.09	1.22	11COT	-1.95	0.16	0.22	1.97

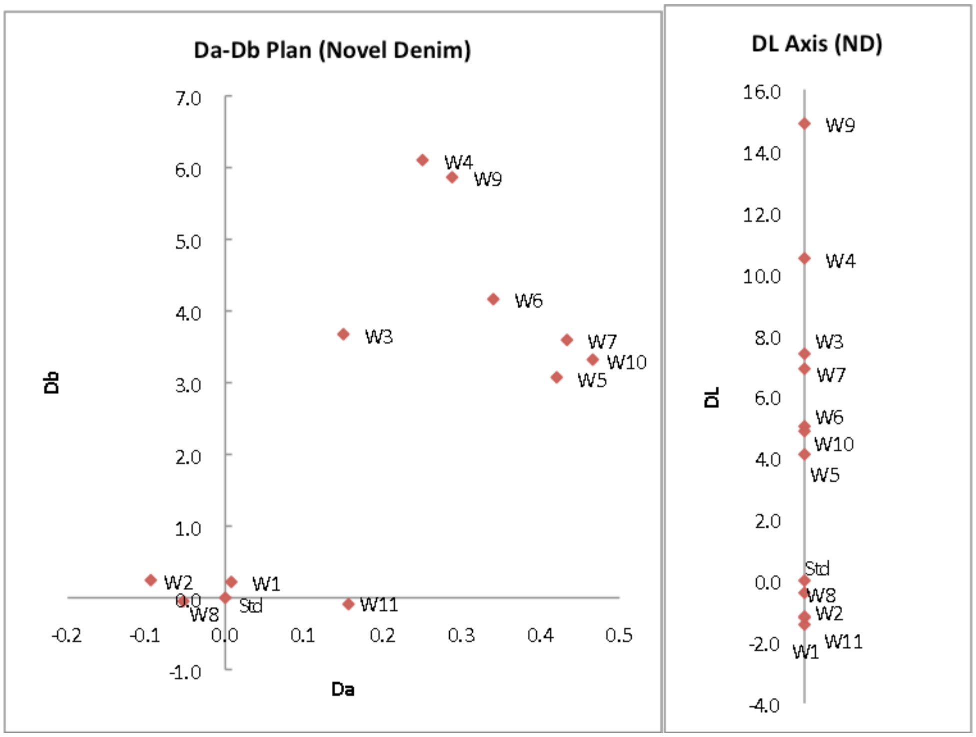

Figure 4-15 Comparison of washed and un-washed denim samples

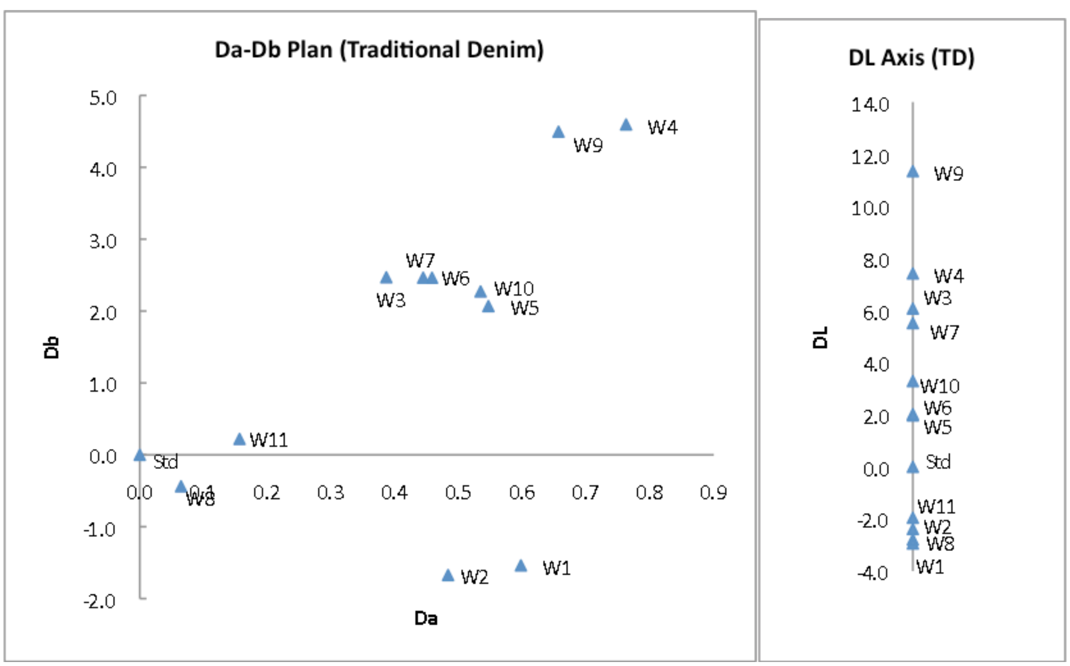

Figure 4-16 Evaluation of washed Conventional denim samples in Da-Dband DL plans compared to untreated sample

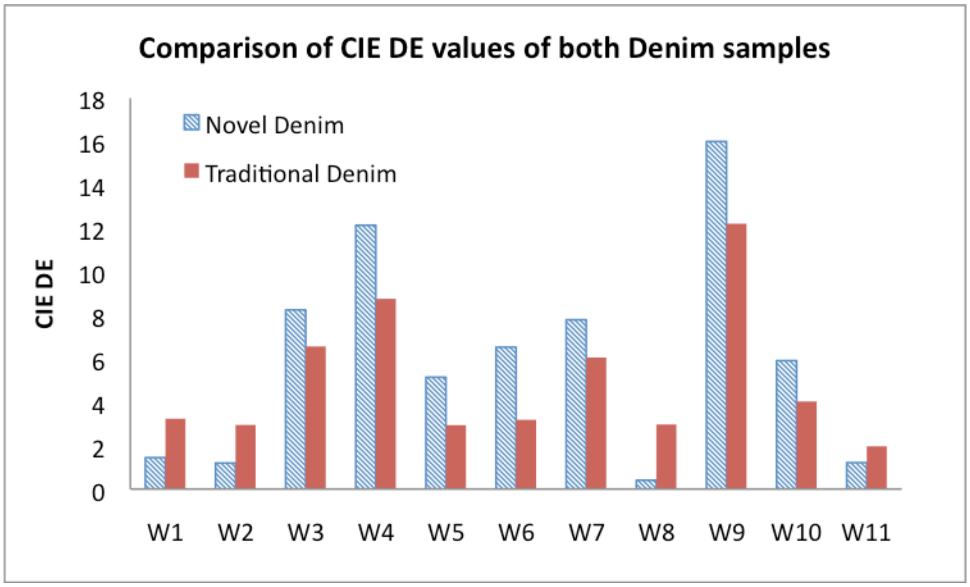

Figure 4-17Comparison of CIE DE values of denim samples

From the Figures 4-16 and 4-17 it can be observed that W4 (desized, bleached and applied silicone softener) and W9 (desized, bleached, enzyme and stone washed) made a significant influence as compared to other industrial washes, on the colour of both the denim samples regardless their structures. Samples have shifted much more towards orange hue with increased lightness. This phenomenon causes a major effect on CIE DE value.

Figure 4-17 also shows that changes in colour of the novel (functional) denim samples are much more severe as compared to Conventional denim samples. It can also be seen that with some washes like W1, W2, W8 and W11, the change in colour is almost negligible.

We can derive following conclusion from all above discussion that two different denims, which have been produced by using two different weft yarns, show variation in reflectance after passing through different washing process. CIE Lab parameters and Δ E were selected to do a comparison.

Nevertheless, in case of value a*, there is a significant difference and correlation is quite low. Furthermore, study concludes that major variation is linked with bleaching process, whereas, enzyme treatment makes insignificant changes. Moreover, stone washing creates moderate variation in colour. This work provides a guideline to denim manufacturers during the finalization of washing process.

4.14 Comparison of conventional and functional denim subjective evaluation

For this study subsequent procedure was adopted for subjective evaluation of two different types of denims:

1. Two denim samples were prepared for testing.
2. Six areas were marked for evaluation and comparison of the hand (tactile comfort) values.
3. Evaluation sheets were prepared by using ordinal scale 1-7 (1 means poor property, 7 means excellent property).
4. People were chosen indiscriminately from different social groups. There were total 30 people (18 males and 12 females).
5. Selected evaluating people were deeply informed about the importance of the tests in question and ways to provide their observation.
6. A closed evaluation box has been used so that people should give their feeling without visual observation of the denim samples. This was done to avoid any influence of the sample visual appearance.
7. Air-conditioned rooms, where the temperature was between 20-22° C and relative humidity was 24-26 % were used to record the observations.

The objective of the study is to find any diversity between the two different denim fabrics. Tactile properties of fabric have a strong link with its construction, type of yarn (ring, rotor or friction), and twist level of yarn. Keeping it in view we have selected questions to investigate the impact of weft variation.

Keeping it in view, following six questions were formed:

1. What is your opinion about the overall comfort of this sample?

2. Do you feel that the fabric surface is smooth?
3. Do you feel that the fabric is stretchable?
4. In initial two seconds, do you feel that the fabric is cool?
5. Do you feel that the fabric is handful and bulky?
6. Do you feel that the fabric is soft?

Evaluating people were previously informed about the evaluation procedure and the way of judgment, and they were asked to give their judgment within the scale of 1-7. One means the lowest value, while seven means the highest value.

Thirty observers were engaged in the evaluation process of comparison of two denim fabrics consisting of different weft yarn. Group of observers consists of 60% male and 40% female. Their age ranged from 18 years to 48 years. Minimum education criteria were graduation or people who are doing their graduation. This precaution was adopted to have a mature evaluation. Furthermore, all observers were users of denim clothing.

We can derive following conclusions from the Table 4.25:

1. People feel that overall comfort of conventional is higher than the functional denim.
2. Surface of functional denim is smooth as compared to conventional denim.
3. Functional denim is more stretchable as compared to conventional denim.
4. Functional denim provides a cool effect. It is an indicator that conventional denim keeps the body warm as compared to functional denim.
5. People view that conventional denim is bulky in nature.
6. Conventional denim is softer (more compressible) in comparison to functional denim.

The most important factor in all above discussion is the overall comfort. People identified a difference between conventional and functional denim. This result provides enough evidence to develop functional denim, which may be able to replace conventional denim.

Table 4-24 Kendall's concordance W of conventional and functional denim

Questions	SSR	W	K (n-1)	$x^2_{0.05}$ *(n-1)*
What is your opinion about the overall comfort of the sample?	163.37	0.00569	2.11	0.00345
In initial two seconds, do you feel that fabric is cool?	174.17	0.0155	2.25	0.00335
Do you feel that fabric is handful and bulky?	125.37	0.0139	1.62	0.00335
Do you feel that fabric is soft?	95.37	0.0047	1.23	0.00335
Do you feel that fabric surface is smooth?	155.47	0.0049	2.01	0.00335
Do you feel that fabric is stretchable?	83.47	0.0034	1.08	0.00335

Table 4-25 Median comparison of functional and conventional denim

Question	Median (Conventional Denim)	Confidence Boundaries Low-High		Median (Functional Denim)	Confidence Interval Limits Low-High	
What is your opinion about overall comfort of this sample?	4.17	3.23	5.06	3.50	2.61	4.39
Do you feel that fabric surface is smooth?	3.36	2.59	4.12	3.50	2.61	4.27
Do you feel that fabric is stretchable?	2.80	2.26	3.23	3.70	3.16	3.97
In initial two seconds, do you feel that fabric is cool?	3.88	3.26	4.55	3.93	3.11	4.70
Do you go through that fabric is handful and bulky?	2.37	2.01	3.06	2.09	1.77	2.40
Do you think that fabric is soft?	5.00	4.41	5.55	5.05	3.56	5.54

4.15 Influence of cationic and silicone softeners and weft variation on thermal and sensorial characteristics of denim subjective and objective evaluation

Denim manufacturers apply certain textile auxiliaries on denim clothing in industrial clothing washing process to impart assured properties. Such treatment modifies the thermal and sensorial characteristics of denim clothing. For this study there are two sets of denim; conventional denim by using cotton yarn as warp, weft, and functional denim by using cotton yarn as warp and Spun PP yarn as weft. These sets were desized, rinsed, bleached and treated with cationic and silicone softeners. Impact of weft variation and application of two distinct softeners was studied. This investigation was carried out by using Alambeta and by conducting a survey. Study finds that in both cases people prefer hand feel of denim treated with silicone softener as compared to cationic softener. Moreover, people state that conventional denim treated with silicone is less cool, which is also verified by Alambeta. However, in case of functional denim, there is a contradiction in the views of people and Alambeta results. Maybe the changed fabric friction affected the feeling of the testing persons.

Table 4-26 Kendall's Concordance W conventional and functional denim treated with silicone and cationic softeners

Questions	**SSR**	**W**	**K (n-1)**	$x^2_{0.05}(n-1)$
What is your opinion about overall comfort of the sample? (conventional denim)	139.2	0.004129	1.796	0.00335
In initial two seconds, do you feel that fabric is cool? (conventional denim)	113.47	0.003366	1.464	0.00335
What is your opinion about overall comfort of the sample? (functional denim)	161.87	0.004801	2.088602	0.00335
In initial two seconds, do you feel that fabric is cool? (functional denim)	208.30	0.006179	2.687742	0.00335

Table 4-27 Median and 100(1-A) confidence interval of conventional denim

Question	Median (Cationic Softener)	Confidence Boundaries Low	High	Median (Silicone Softener)	Confidence Interval Limits (Low-High)	
		Low	High		Low	High
What is your opinion about the overall comfort of the sample? (conventional denim)	4.75	3.83	5.42	6.17	5.27	6.76
In initial two seconds, do you feel that fabric is cool? (conventional denim)	4.05	3.56	4.55	3.90	3.30	4.44
What is your opinion about the overall comfort of the sample? (functional denim)	5.17	4.76	6.06	5.50	4.90	6.17
In initial two seconds, do you feel that fabric is cool? (functional denim)	3.94	3.35	4.55	4.50	3.61	5.39

4.16 Summary and future direction

Summary of the results is as under:

Thermal resistance prediction model to determine thermal resistance under wet conditions is one of the most consequential outcomes of the whole study. This model has been developed considering that fabric is composed of yarn (warp and weft) of same or of more than one kind of fibre, moisture and air. Share of warp and weft in total yarn consumption, inter fibre and inter yarn porosity, fabric and fibre density, share of air and moisture have been simulated. Moreover, three possible arrangements of resistances have been considered. Simulated values correspond to the measured valued. Based on this observation, it can be said that this model can predict thermal resistance of any fabric made by using hydrophobic or hydrophilic or by using both materials under wet conditions.

Second most significant outcome is the development and testing of functional denim. Functional denim made of cotton and Spun PP keeps its thermal resistance property in wet conditions better than conventional denims, even better than denim made by using cotton as warp and AT PP, SBC PP and PET as weft. It means it will keep the human body warm for longer time in wet and cold climate. Denim made by using Spun PP has highest level of overall moisture management capacity, lowest bending rigidity and highest airflow. Besides, in subjective evaluation people did not find a big difference in overall hand-feel of conventional denim made of 100% cotton and functional denim.

In addition, we found that higher porosity means higher thermal resistance. It shows that replacement of air gaps with polymers will reduce the thermal resistance since polymers have lower thermal resistance than air.

Results authenticate that type of twill weave has no significant influence on thermal parameters (conductivity, resistance, absorbtivity) of denim. There is no change in alignment of the fibres, and rather it was the just arrangement of yarn.

It was educed that there is a significant adaptation in thermal parameters due to the presence of textile auxiliaries. It emerges that one should be attentive while selecting textile auxiliaries to keep thermal parameters under desired limits.

Denims made by Spun PP and AT PP as weft yarn exhibit greater consistencies under wet conditions as compared to denims made by using PET, cotton and SBC PP as weft yarn under wet conditions. Thermal resistance of denims made by using Spun PP and AT PP is 50% higher than other denim samples. It is primarily due to the higher numbers of crimps present in AT PP and plentiful in Spun PP due to short fibres. Presence of pores furnishes air pockets, which have much higher thermal resistance as compared to polymers. This conclusion braces the idea to have less dense fabric for higher thermal resistance.

Moisture Management Tester results fortify that Spun PP has the highest capacity to manage the moisture. Moister Management Tester (MITT) provides Moisture Management Capability (OMMC). This instrument authenticates that Spun PP can manage moisture and does not create a highly wet impression and keeps its dryness intact. AT PP is keeping the second position in the list after Spun PP. Remarkably, Denim with Spun PP and AT PP provide better thermal comfort while a user is in sitting position.

KES was used to measure friction and geometrical roughness. It is visible from the results that coefficient of friction of filaments is lower than the staple. Air texture, SBC and PET have low values as compared to cotton and Spun PP. There is the same case with the geometrical roughness. Denim made by SBC PP posses the lowest geometrical roughness, nevertheless, cotton is second to it and Spun PP follows.

Vapour permeability of fabric helps to keep the skin dry under a wet condition, particularly in case of sweating it plays a critical role. Apparently, there is no set pattern in the response of different denims. We come upon a scattered picture, which registers that there are many factors, which are causing the vapour permeability. Nonetheless, denim made by cotton has lesser vapour permeability resistance.

Denim made by cotton and Spun PP has the highest airflow it is mainly due to the staple fibres used to make these yarns. Notwithstanding, industrial washing process has no set pattern. Results demonstrate that staple fibre provides better flow of air, which has a fundamental role in the clothing comfort phenomenon.

Bending force represents the bending rigidity of any material. Results tell about the bending force of different denims. It is self-evident from the table that in both cases; warp and weft, Spun PP has the lowest bending force, which means that it creates fewer hindrances in the movement of a body.

Results show that there is a significant diversification among different denim samples. Denim made by cotton and Spun PP has the highest airflow, it is mainly due to the staple fibres used to make these yarns. Nevertheless, industrial washing process has no set pattern. Results show that staple fibre provides better flow for air, than filaments.

Subjective evaluation was conducted to verify the results derived from objective measurement. One of the main confirmations is cooling effect of denim. Thermal absorbtivity of Spun PP is less as compared to cotton, and it is verified during subjective evaluation that people feel that cotton denim is cooler than Spun PP denim. In general, people feel that Spun PP denim is softer and smooth. However, conventional denim is preferred in the area of overall comfort when it is compared with Spun PP denim.

Study finds that people prefer the hand feel of denim treated with silicone softener as compared to cationic softener. Moreover, people state that conventional denim treated with silicone is less cool, which is also verified by Alambeta. However, in case of functional denim, there is a disagreement in the views of people and Alambeta results.

4.17 Future research direction

1. Mathematical equation has been developed to predict thermal resistance of fabric under different wet condition. There is a need to work to find out the exact relationship between

thermal conductivity and moisture in the fabric taking into account the interaction between water and cotton.

2. Spun PP gives much better results but denim made by it has a very uneven surface due to the presence of polypropylene outstanding fibres. These fibres cannot be removed by passing fabric through a singeing machine or by treating with enzymes. There is a need to develop technology to have a clean and shining surface like conventional denim so that it should fulfil the psychological comfort of the people.

3. AT PP filament is second to Spun PP. Denim made by AT PP does not create a big issue in surface look. It has no free ends and AT PP can replace Spun PP. Nevertheless, cotton loose ends can be removed by using strong enzymatic treatments.

4. In this study, a fix percentage of polypropylene was used. It is suggested that by using different percentages of polypropylene and cotton, denim should be made. It is hoped that most optimum combination could be determine.

5 Work of author

Author of this report has completed 12 research papers and reports, which are related to this issue. A brief summary is here under:

5.1 Journal Publications (accepted)

1. Mangat, M. M., Militky, J. and Hes, L.: Mathematical model for thermal resistance of fabric under dynamic moisture conditions, Journal of Fibres and Textile, 2012
2. Magnet, M. M., Husain, T. and Bajzik, V.: Impact of Different Weft Materials and Washing Treatments on Moisture Management Characteristics of Denim. The Journal of Engineered Fibres and Fabrics (April 2012)
3. Bajzik, V. Mangat. M. M., and Hes, L., Effect of Two Types of Softeners and Weft Composition on Thermal Comfort Characteristics of Denim Fabrics. Journal of Fibres and Textile., Accepted for publication (April 2012)
4. Abbasi, A.M.R., Mangat. M. M., Baheti, V. K., and Militky, J. Electrical and Thermal Properties of Polypyrrole Coated Cotton Fabric, Journal of Fibres and Textile. Accepted for publication
5. Mangat, M. M., Wiener, K. and Rehan, A.M.R., Evaluation of changes in colour of denim after various industrial washings with different fibre compositions, Journal of Fibres and Textile, Accepted for publication

5.2 Journal Publications (under consideration)

6. Hes, L., and Mangat, M.M., Influence of Moisture Variation on Thermal Parameters of Conventional and Functional Denim. *Journal of Engineered Fiber and Fabric*. Under review.
7. Mangat, M.M., Havelka, A., and Fleglova, Z, *Sensorial Comfort Appraisal of Denim by Objective Assessment of Surface Mechanical Characteristics.* Under review Journal of Fibres and Textile

5.3 Conference papers:

[1] Hes, L. and Mangat, M. M.: Effect of industrial washing on thermal comfort. In: *7th International Textile Conference - TEXSCI 2010* Liberec, 2010.

[2] Mangat, M. M., Bajzik, V. and Hes, L.: Influence of Cationic and Silicone Softeners and Weft Variation on Thermal and Sensorial Characteristics of Denim Subjective and Objective Evaluation. In: *Proceedings of the COVITEX 2011*, Pakistan 2011.

[3] Mangat, M. M., Hussain, T., Hes, L. and Mangat, A. E.: Effect of Denim Clothing Finishing Processes on Physical Characteristics of Denim Fabric. In *Proceedings of the AUTEX 2010*, Lithuania 2010.

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[7] Mangat, M. M., Wiener, K. and Rehan, A.M.R., Evaluation of changes in colour of denim after various industrial washings with different fibre compositions. In: *Proceedings of the COVITEX 2011*, Pakistan 2011.

5.4 Under preparation

[1] Mangat, M. M., Bajzik, V. and Hes, L.: Thermal properties of fleece fabric of different composition under wet conditions
[2] Mangat, M. M., Bajzik, V. and Hes, L.: Impact of compression on thermal properties of denim of different composition under wet conditions
[3] Mangat, M. M., Bajzik, V. and Hes, L.: Impact of compression on thermal properties of fleece fabric of different composition under wet conditions
[4] Mangat, M. M., Bajzik, V. and Hes, L.: Air permeability of fleece fabric of different composition under wet conditions

5.5 Other publications

[1] Mangat, M. M.: Association between Production Capacity and Total Factor Productivity: A Pakistan Knitted Garment Industry Case. In *Proceedings of the 1st International Conference on Textile and Clothing* Lahore 2006.
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